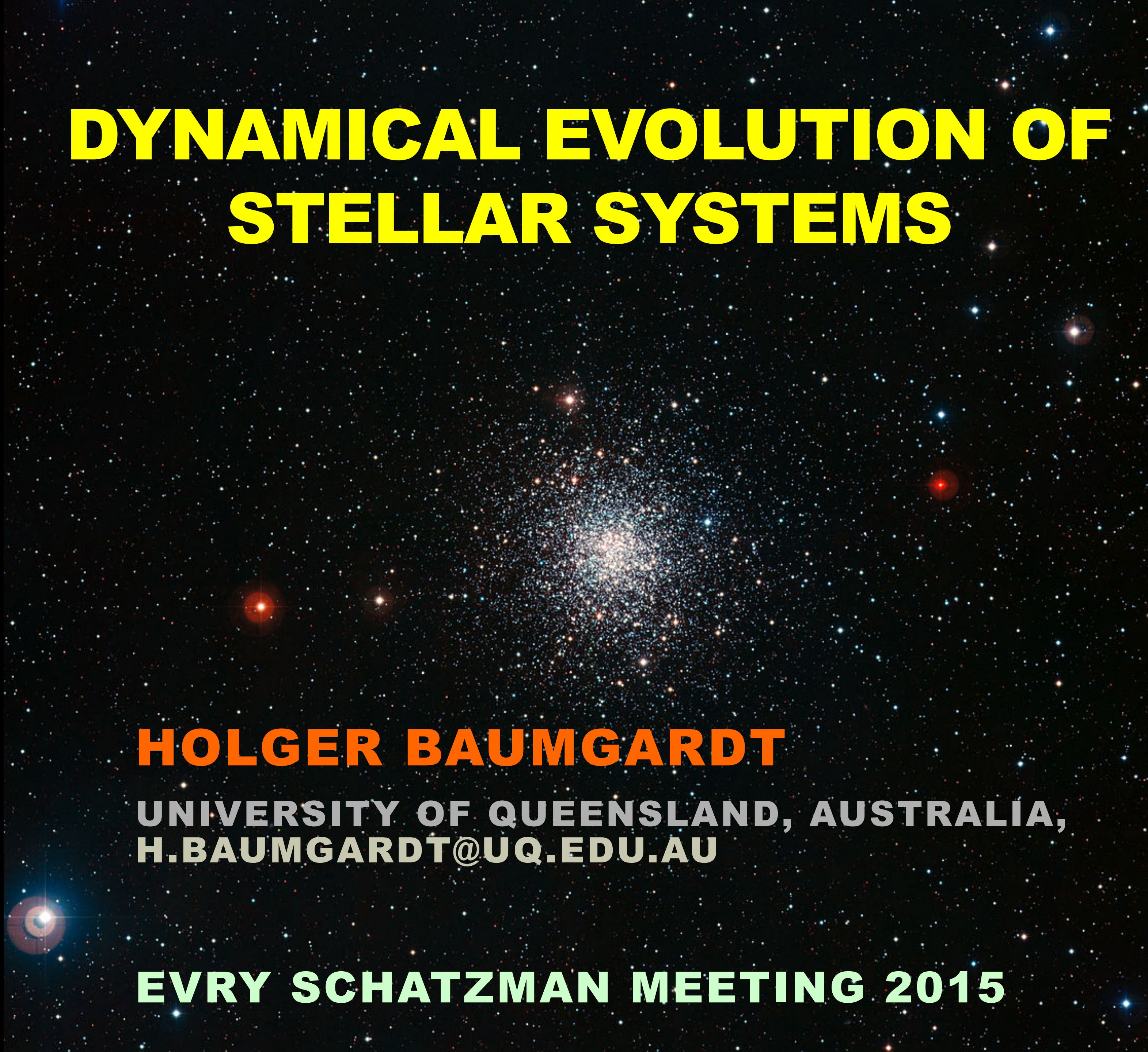


DYNAMICAL EVOLUTION OF STELLAR SYSTEMS

HOLGER BAUMGARDT

UNIVERSITY OF QUEENSLAND, AUSTRALIA,
H.BAUMGARDT@UQ.EDU.AU

EVRY SCHATZMAN MEETING 2015

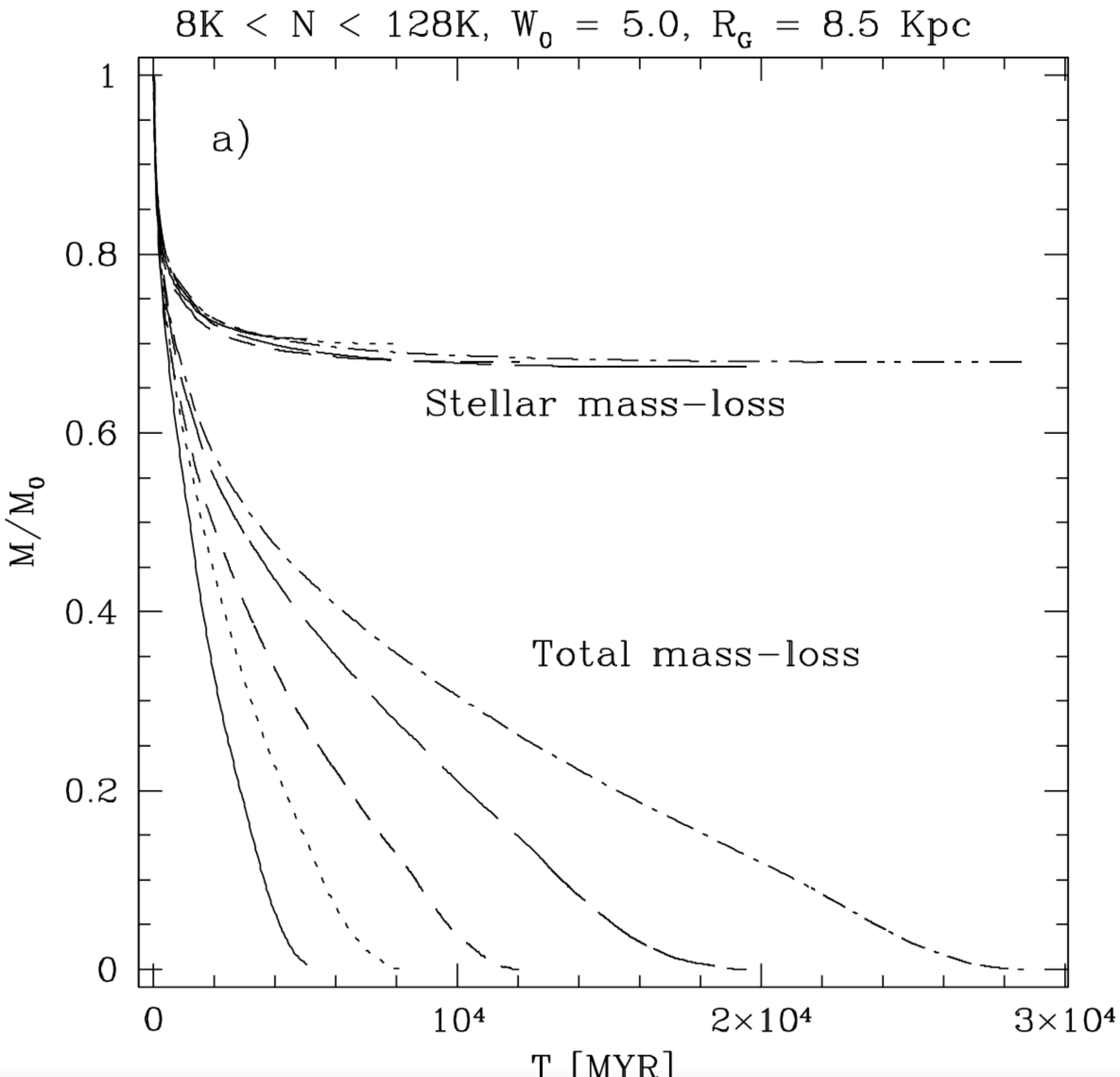
OVERVIEW

- **Lecture 1:**
  - Dynamical Processes in Star Clusters.
- **Lecture 2:**
  - Collapse and two-body Relaxation
- **Lecture 3:**
  - Dissolution of Star Clusters
  - Nuclear Clusters and Massive Black Holes

CLUSTER DISSOLUTION

Evolution of bound mass of star clusters with different mass:

High-mass clusters live longer.



CLUSTER DISSOLUTION

Dissolution time of star clusters in a spherical isothermal galaxy is given by (Baumgardt & Makino 2003):

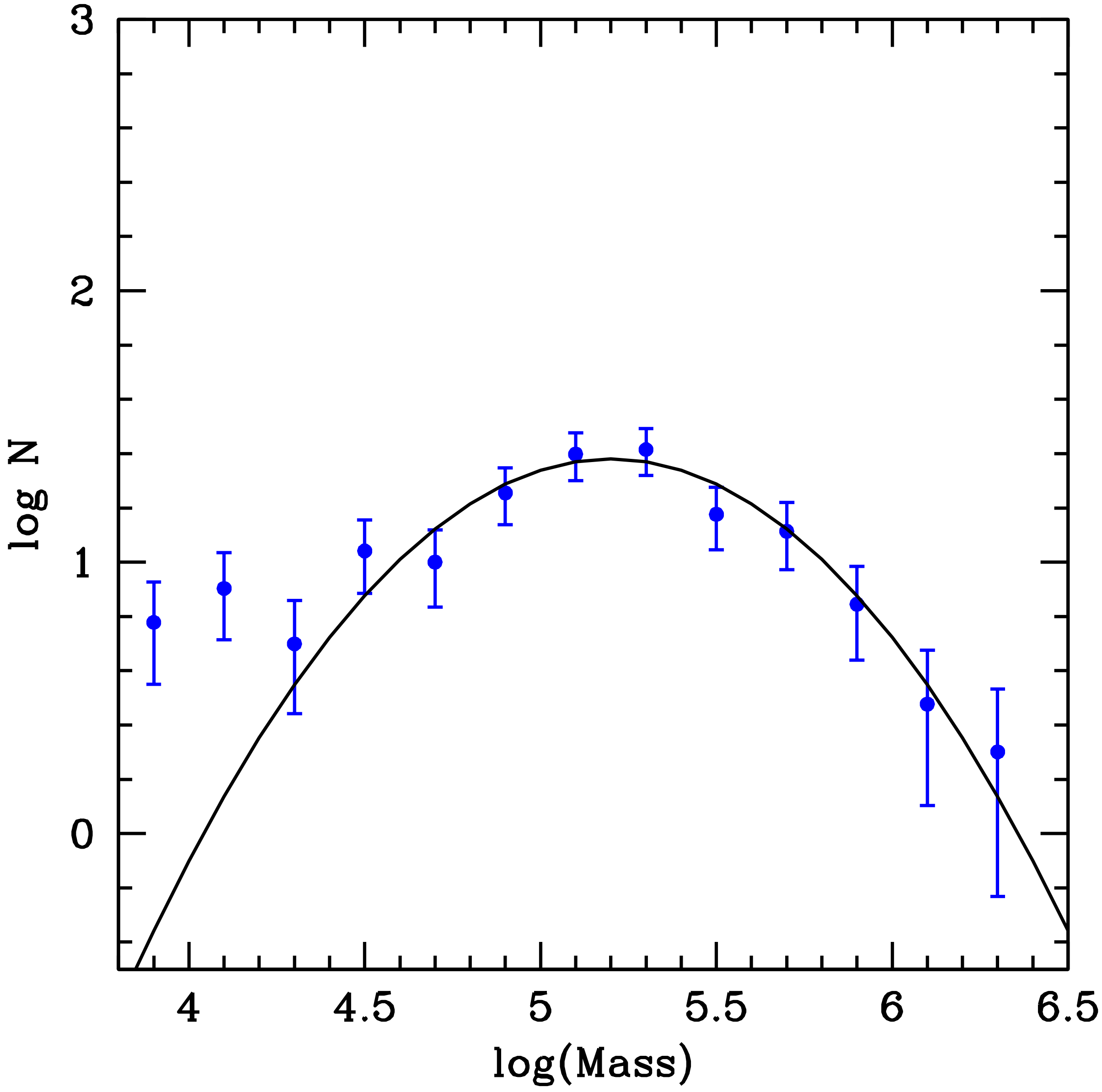
$$\frac{T_{Diss}}{Myr} = 1.9 \left(\frac{M}{\ln(0.02N)} \right)^{0.75} \frac{R_G}{kpc} \left(\frac{V_C}{220 km / \sec} \right)^{-1} (1-\varepsilon)$$

At the solar radius in the Milky Way, all globular clusters with initial masses less than 30.000 $M_\odot$ have completely dissolved. Typical, 10^5 $M_\odot$ globular cluster has lost about 30% of its mass due to dissolution.

Cluster lifetimes are not strongly influenced by initial cluster radius (Gieles et al. 2009), initial binary fraction or initial black hole retention fraction (Lützgendorf et al. 2013).

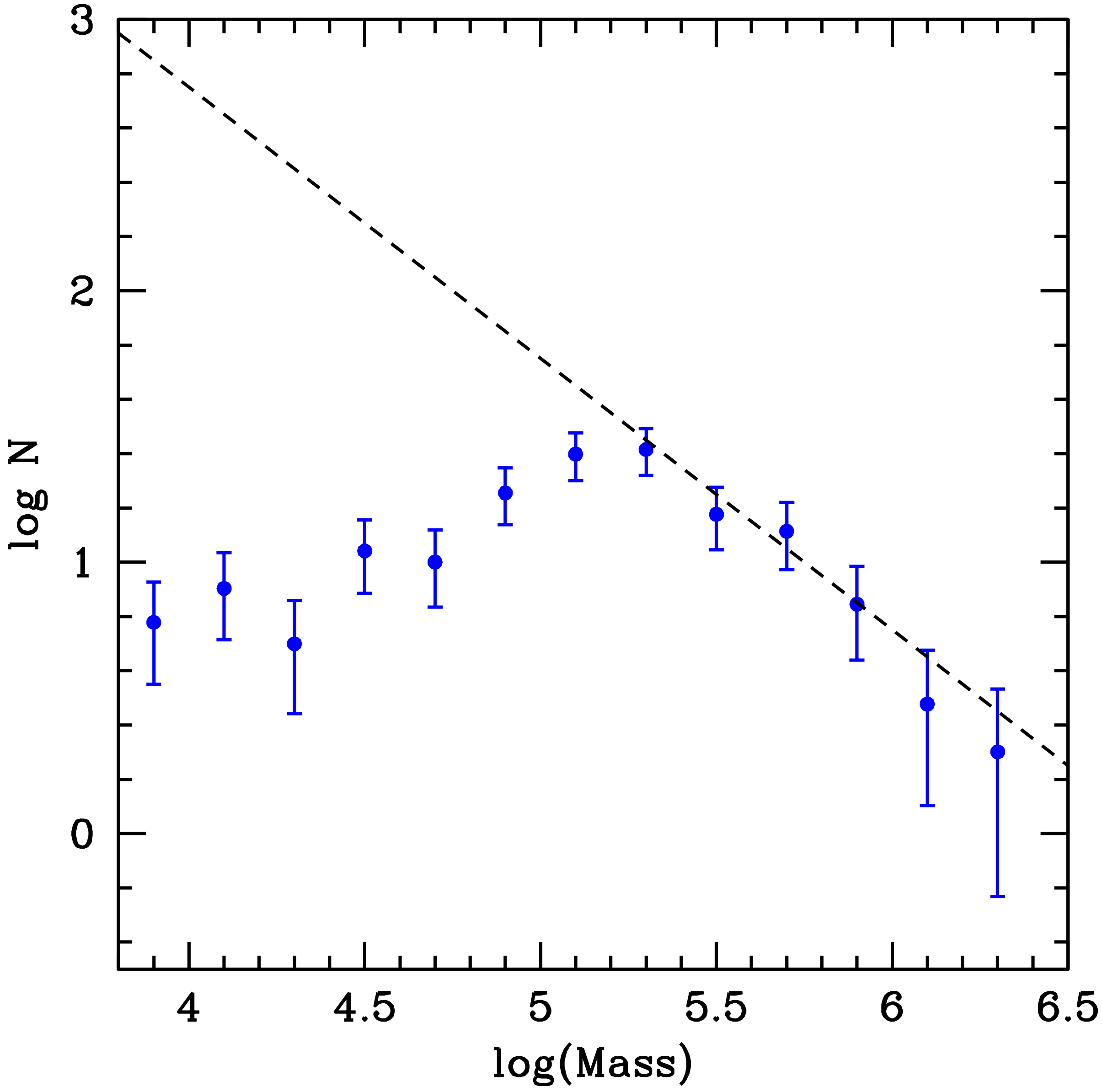
MASS FUNCTION OF MILKY WAY GLOBULAR CLUSTERS

Present-day mass function is a log-normal MF with mean mass around log M=5.2 and a width of σ = 0.5.



MASS FUNCTION OF MILKY WAY GLOBULAR CLUSTERS

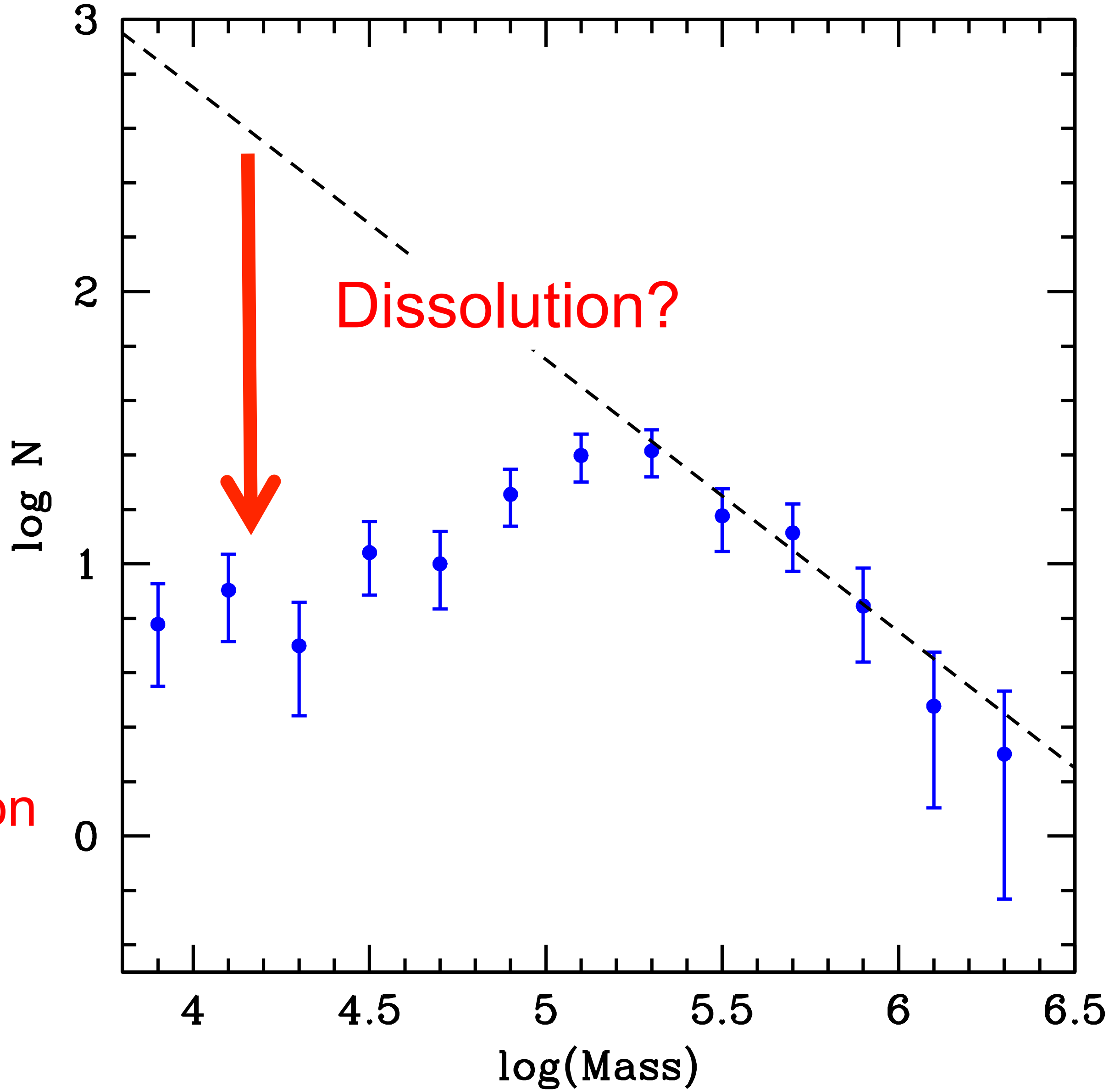
Young star clusters show a power-law mass function with slope α = -2, which fits the GC mass function at the high mass end.



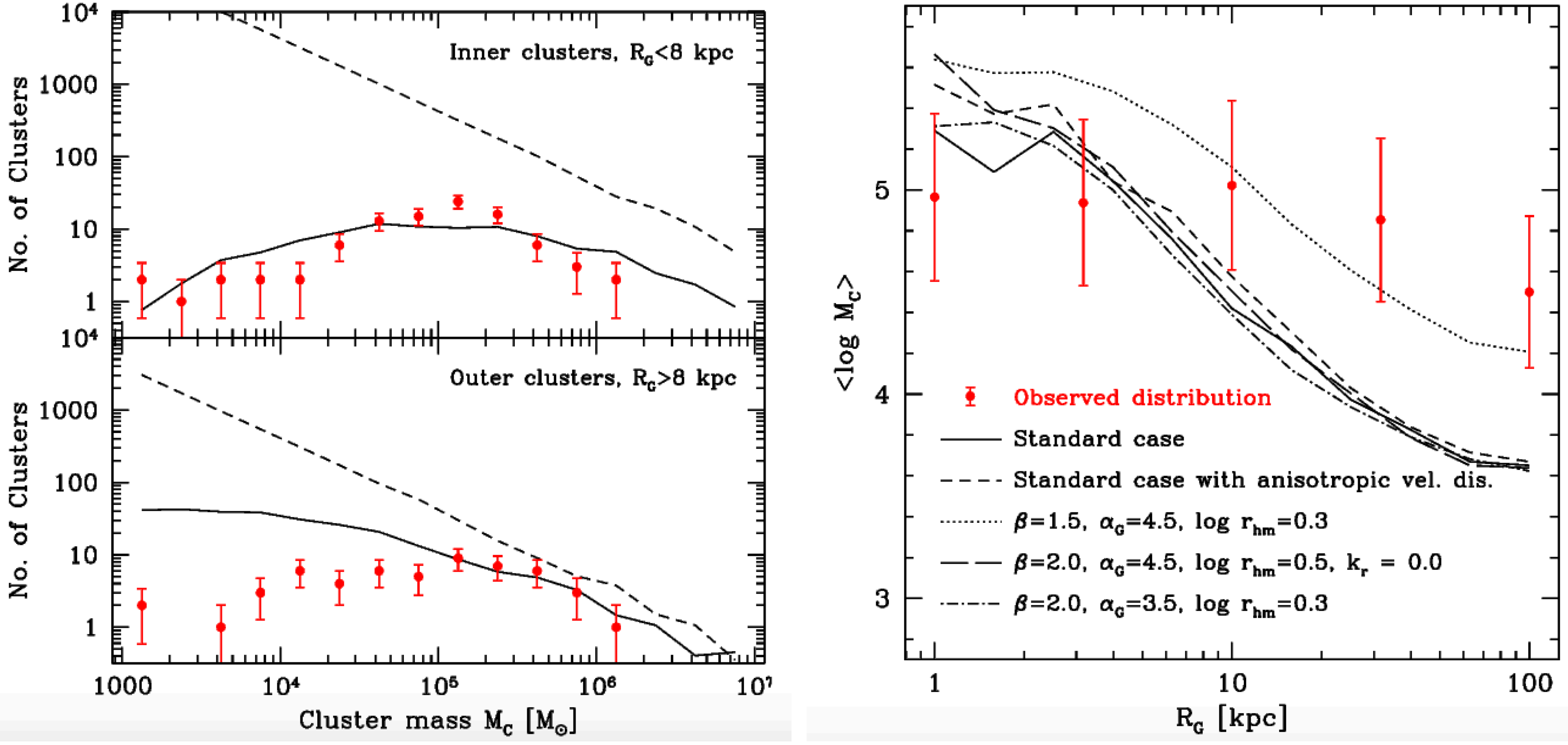
MASS FUNCTION OF MILKY WAY GLOBULAR CLUSTERS

Young star clusters show a power-law mass function with slope α = -2, which fits the GC mass function at the high mass end.

Is the GC mass function due to dissolution?



However this idea faces a problem: If GC dissolution is due to only two-body relaxation and the Milky Way tides, dissolution is too inefficient in the outer parts!



See Vesperini et al. (1998, 2000, 2001), Baumgardt et al. (2008) but also Fall & Zhang (2001) and McLaughlin & Fall (2008) for a different opinion.

Suggested additional dissolution mechanisms:

- ❑ Stellar evolution (Vesperini & Zepf 2003).
- ❑ Primordial gas expulsion (Baumgardt et al. 2008).
- ❑ Tidal shocks from passing molecular clouds (Kruijssen et al. 2012).

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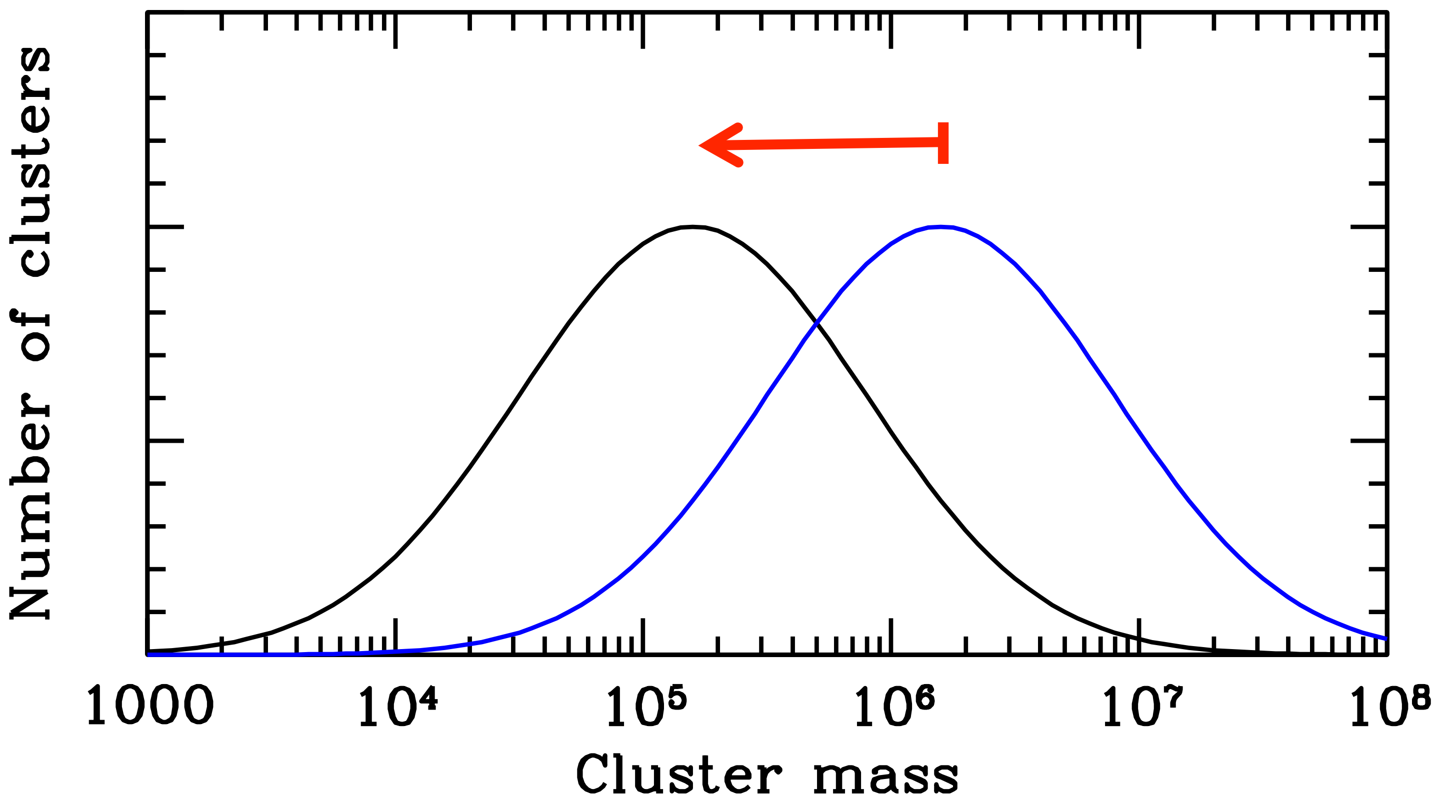
Related questions:

Which fraction of field halo stars come from destroyed clusters?

Only 1% in globular clusters nowadays, if MF was power-law much higher fraction was possible.

Related question:

How does the problem of strong early mass loss of globular clusters that is needed to explain the large fraction of chemically enriched stars in globluar clusters fit into this?



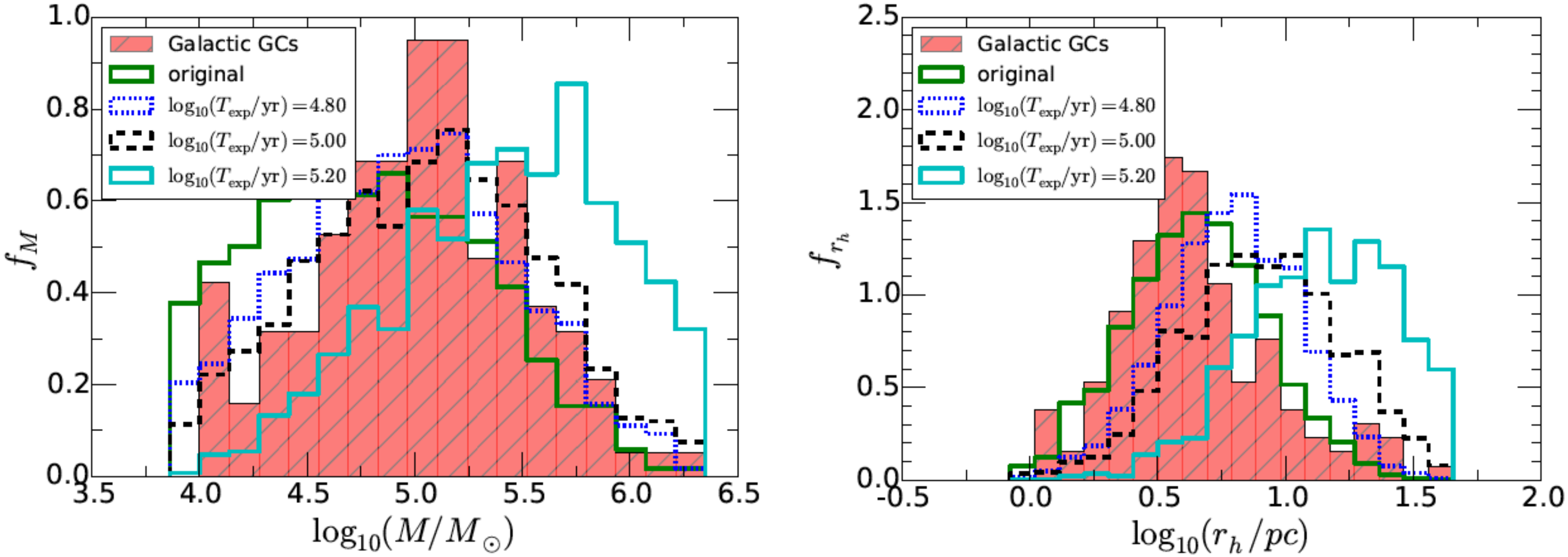
Related question:

How does the problem of strong early mass loss of globular clusters that is needed to explain the large fraction of chemically enriched stars in globluar clusters fit into this?

Large fraction of chemically peculiar stars seen in all globular clusters. This probably points to an inner mass loss mechanism. D'Ercole et al. (2008) investigated mass loss due to stellar evolution.

However their scenario needs a very extended cluster of chemically non-enriched stars (half-mass radius ~ 20 pc).

Strong mass loss might also be caused by early gas expulsion (Khalaj & Baumgardt 2015):



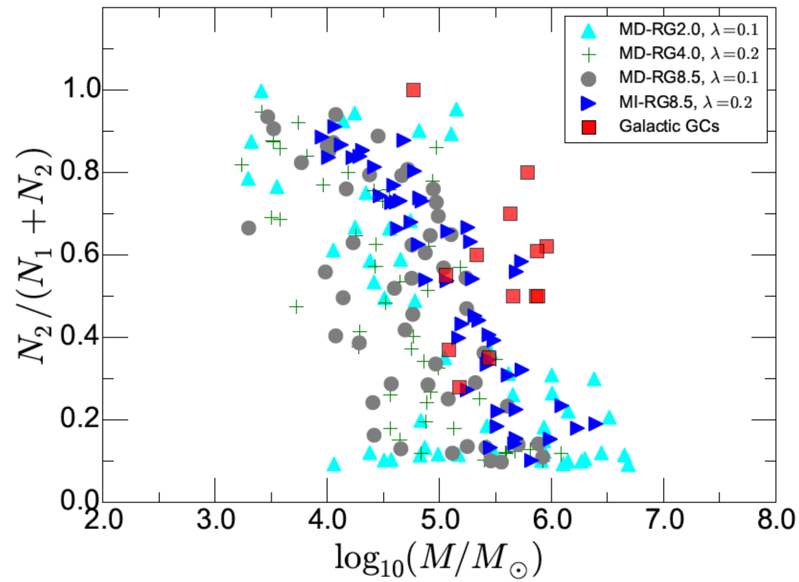
Initial parameters: $\log M = 6.2 \pm 0.3$

$\log r_h = 0.1 \pm 0.3$

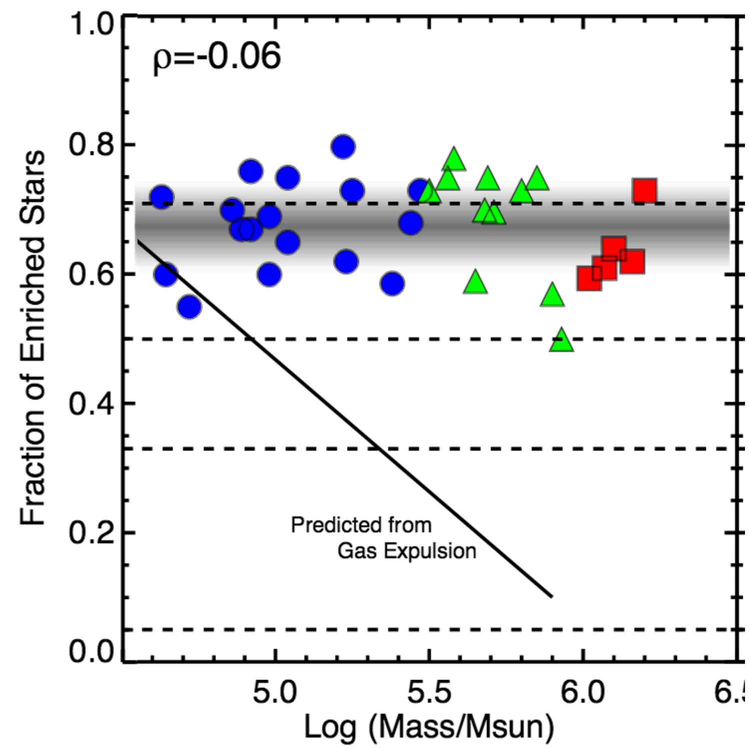
Mean SFE = 50%

$\tau_{Gas} \leq 10^5$ yrs

However our models predict a large spread in the number ratio of enriched stars among different globular clusters.



This is not what is seen in observations (Bastian & Lardo 2015).



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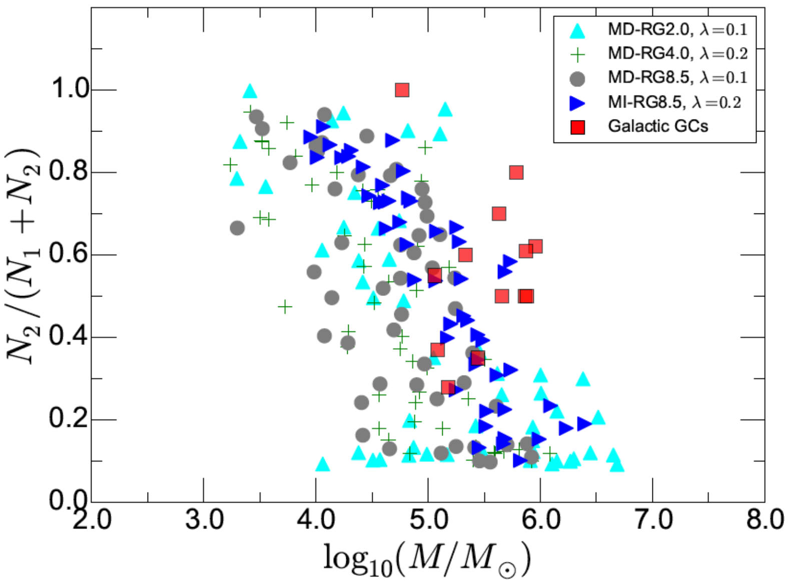

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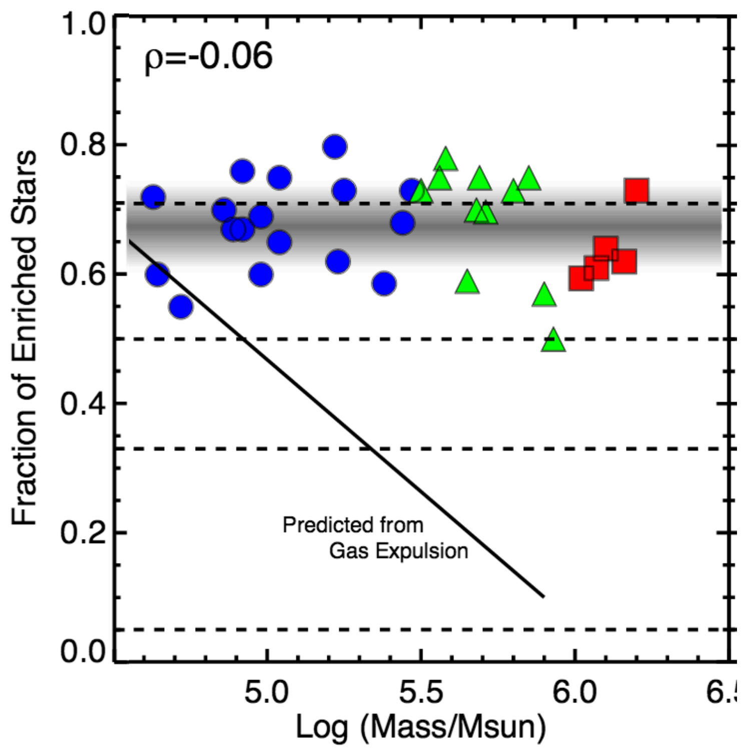
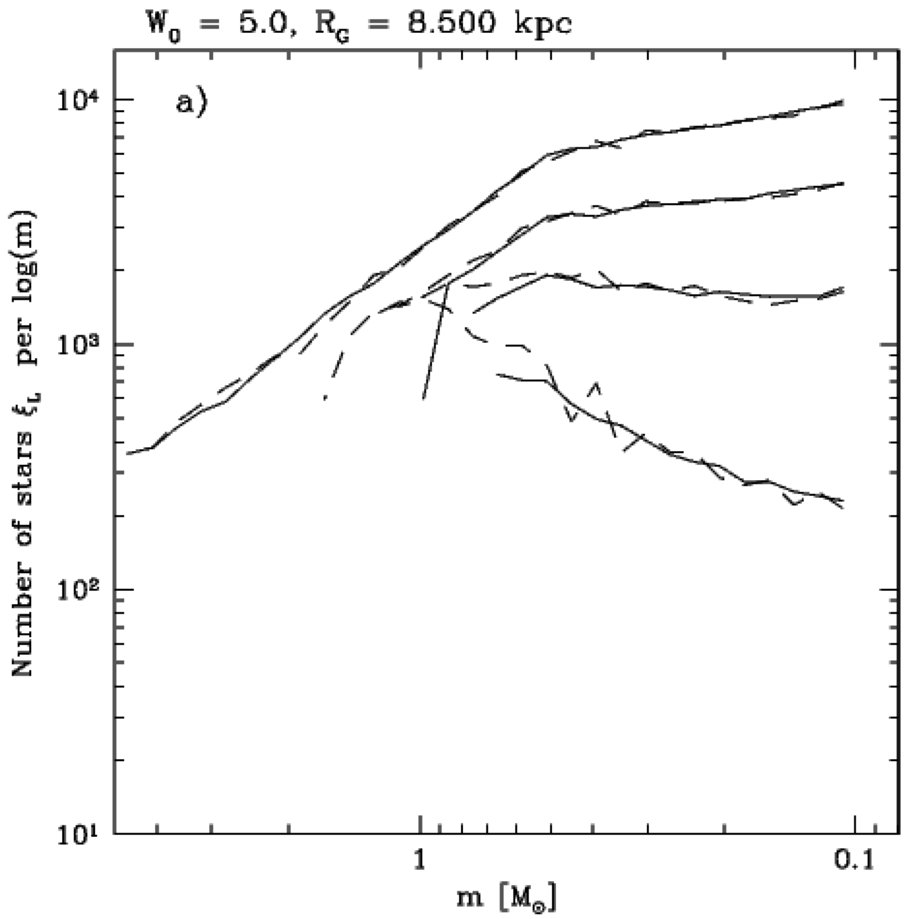


Might indicate that strong mass loss has not happened, but more work is needed.

EVOLUTION OF THE MASS FUNCTION

Due to mass segregation, low mass stars get depleted. The effect is strong enough that close to dissolution the mass function can start to drop towards the lowest masses.



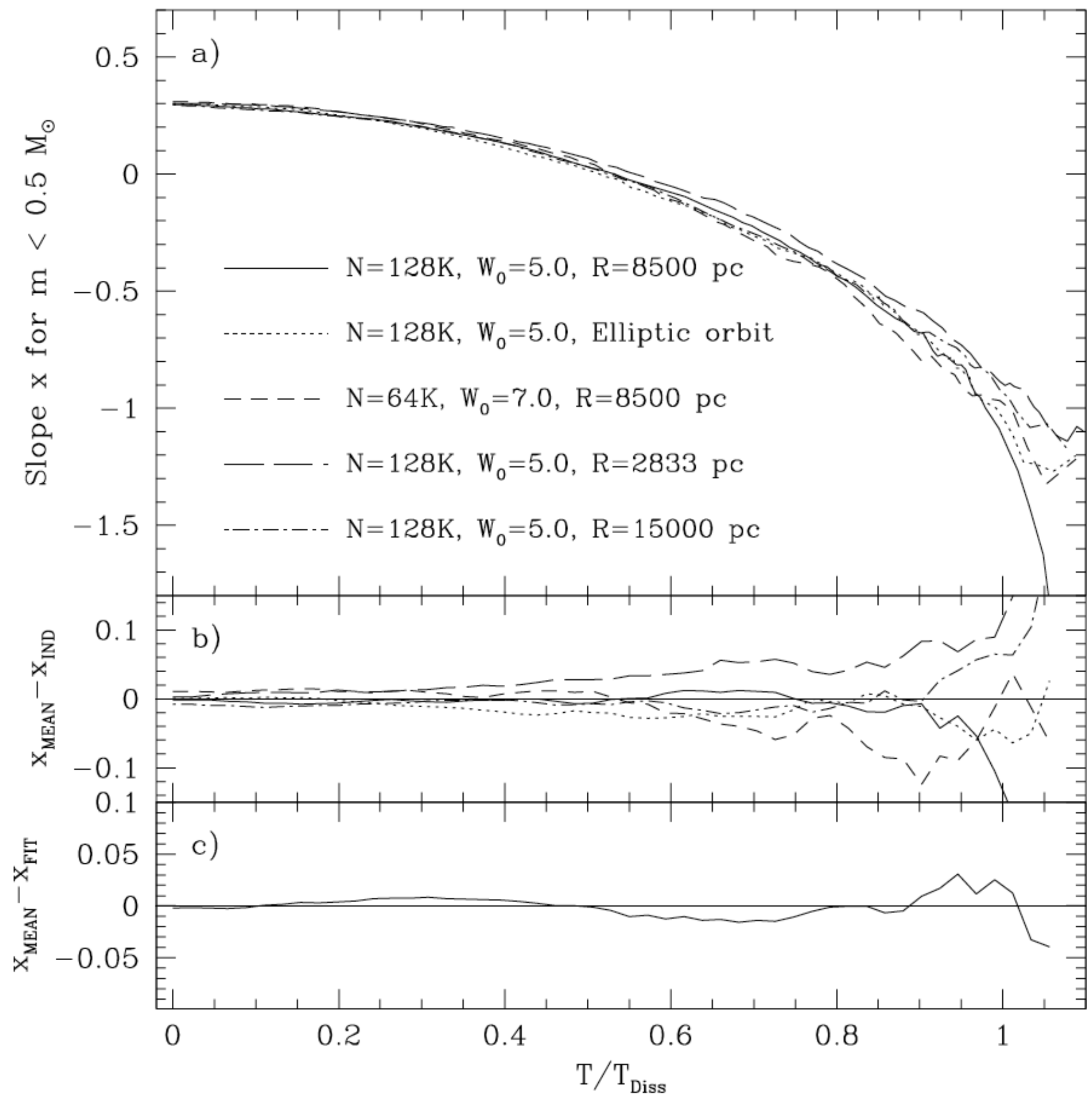
EVOLUTION OF THE MASS FUNCTION

MF slope shows a good correlation with the elapsed time compared to the total lifetime or the relative mass left.

$\alpha = f(T/T_{Diss})$

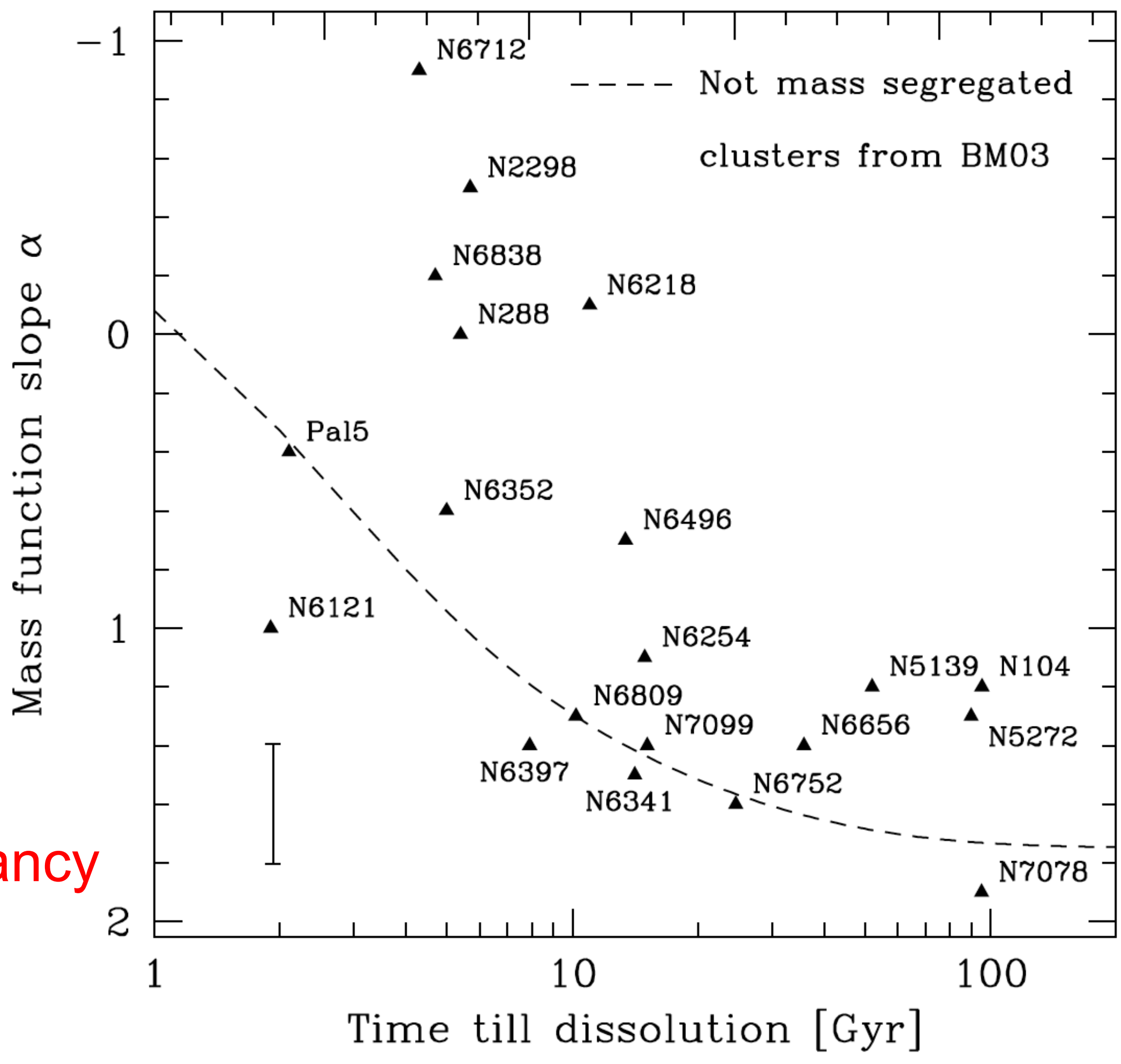
or

$\alpha = f(M(t)/M_{Ini})$



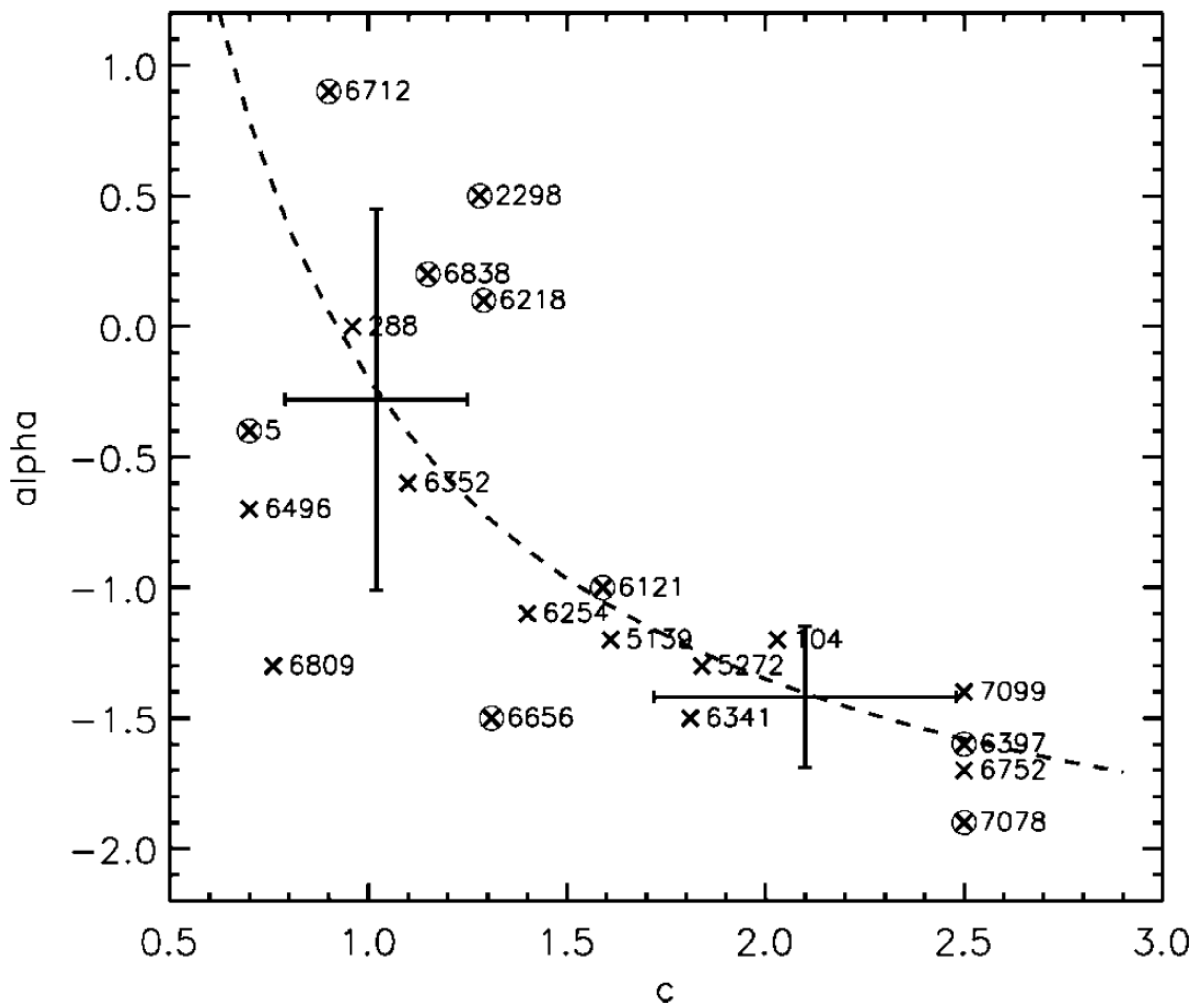
EVOLUTION OF THE MASS FUNCTION

However Galactic GCs seem to have significantly shallower MF slopes compared to what one would expect based on simulations (Baumgardt et al. 2008, Webb & Leigh 2015).



Reason for this discrepancy is unclear…

CORRELATION OF MF SLOPE WITH KING MODEL CONCENTRATION PARAMETER C



from de Marchi et al. (2007)

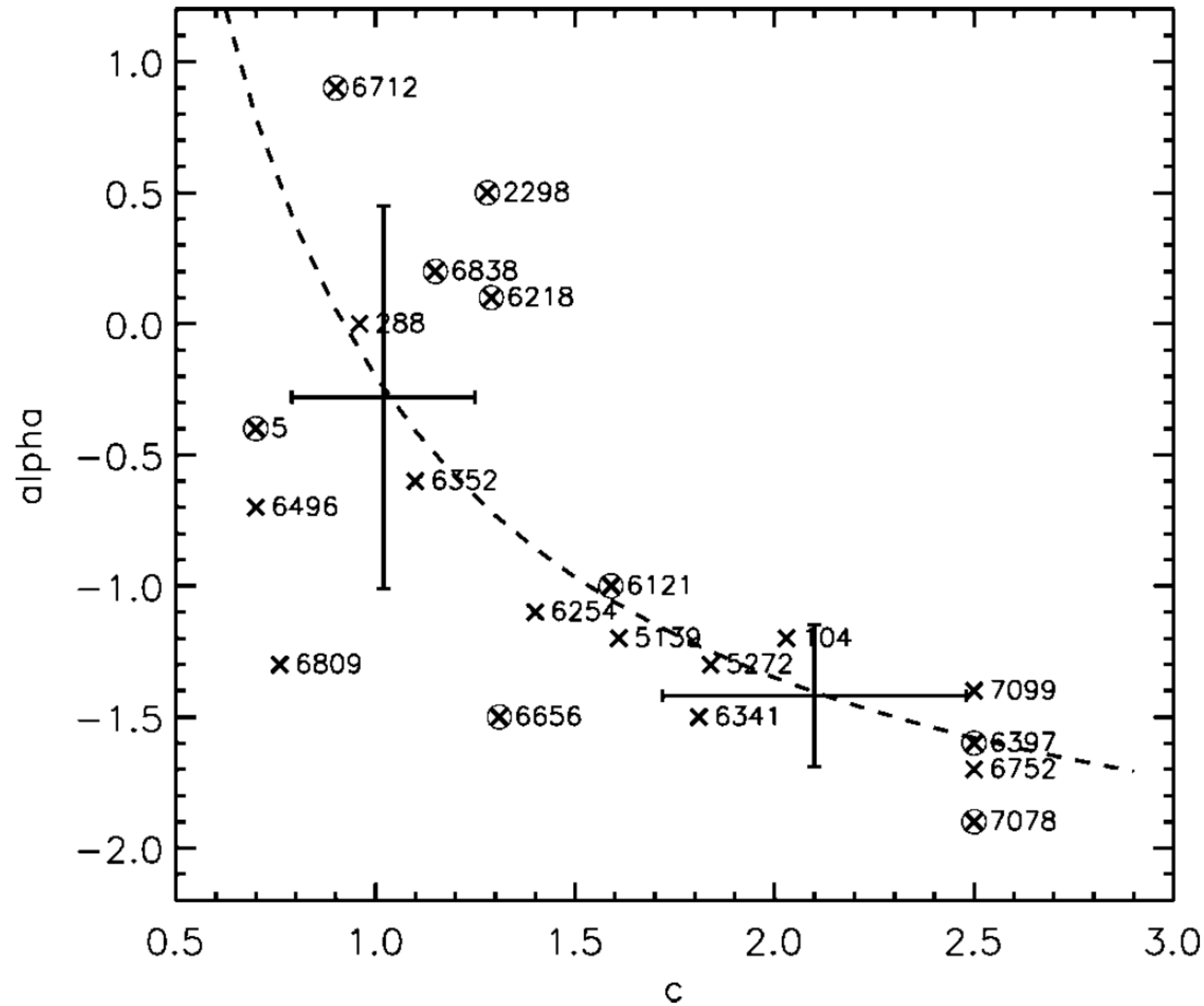
CORRELATION OF MF SLOPE WITH KING MODEL CONCENTRATION PARAMETER C

Selection effect?

Mass segregation?

Stellar binaries?

……

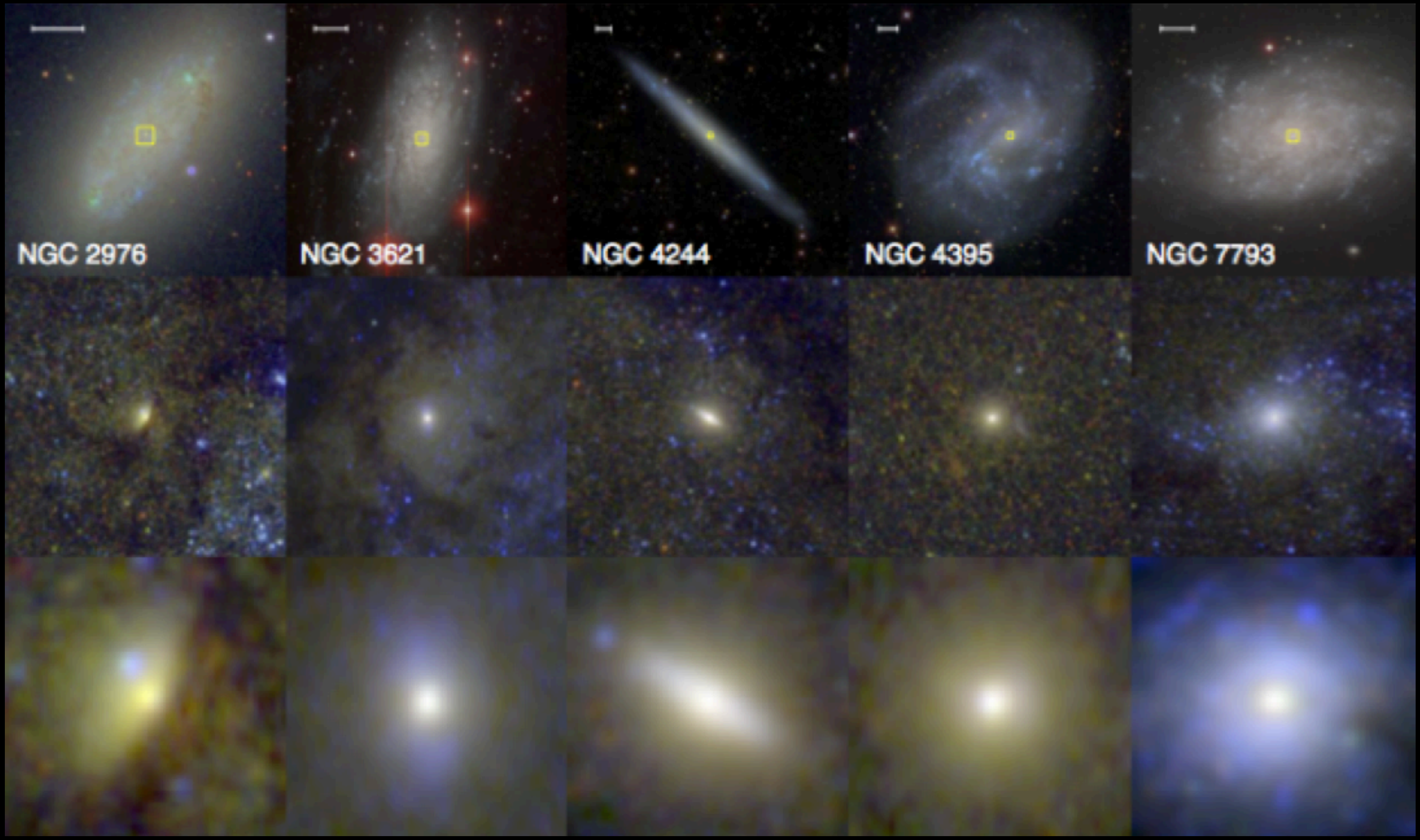


from de Marchi et al. (2007)

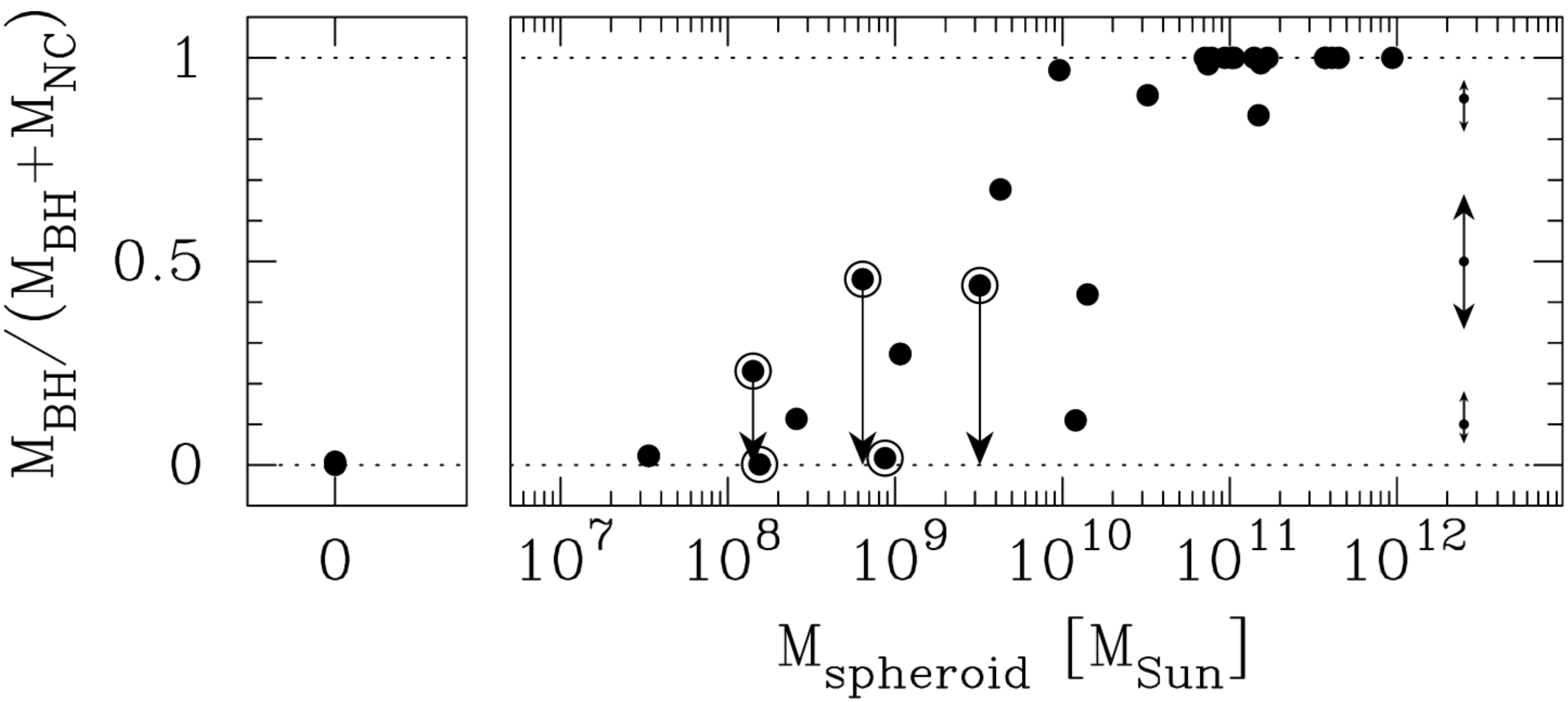
MASSIVE BLACK HOLES

Nuclear star clusters exist in many galaxies (70% of all dE galaxies in Virgo have nuclei, Coté et al. 2006).

The masses of these nuclear clusters are in the range 10^6 to 10^8 solar masses.

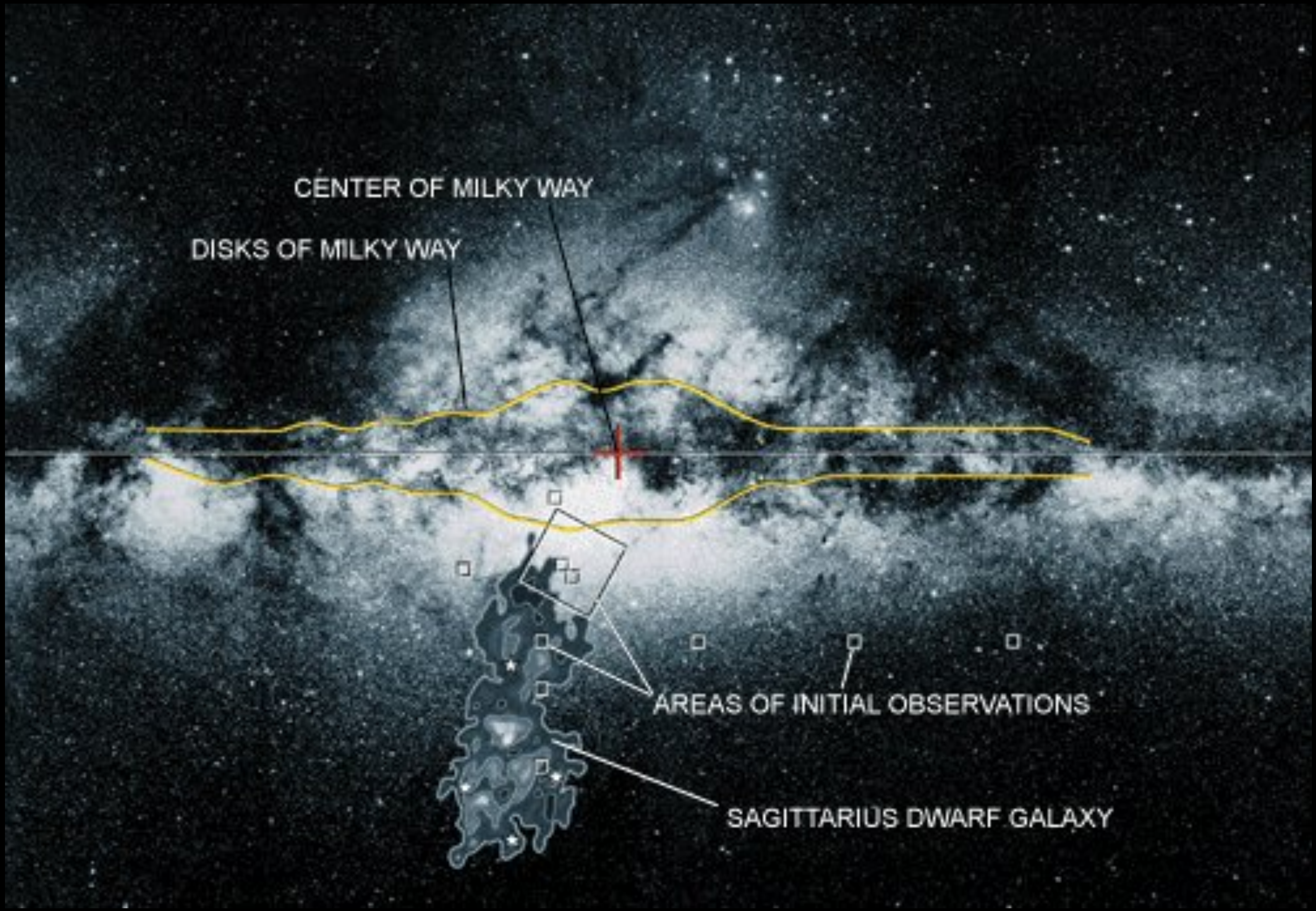


At intermediate masses, the nuclear star clusters co-exist with supermassive black holes:

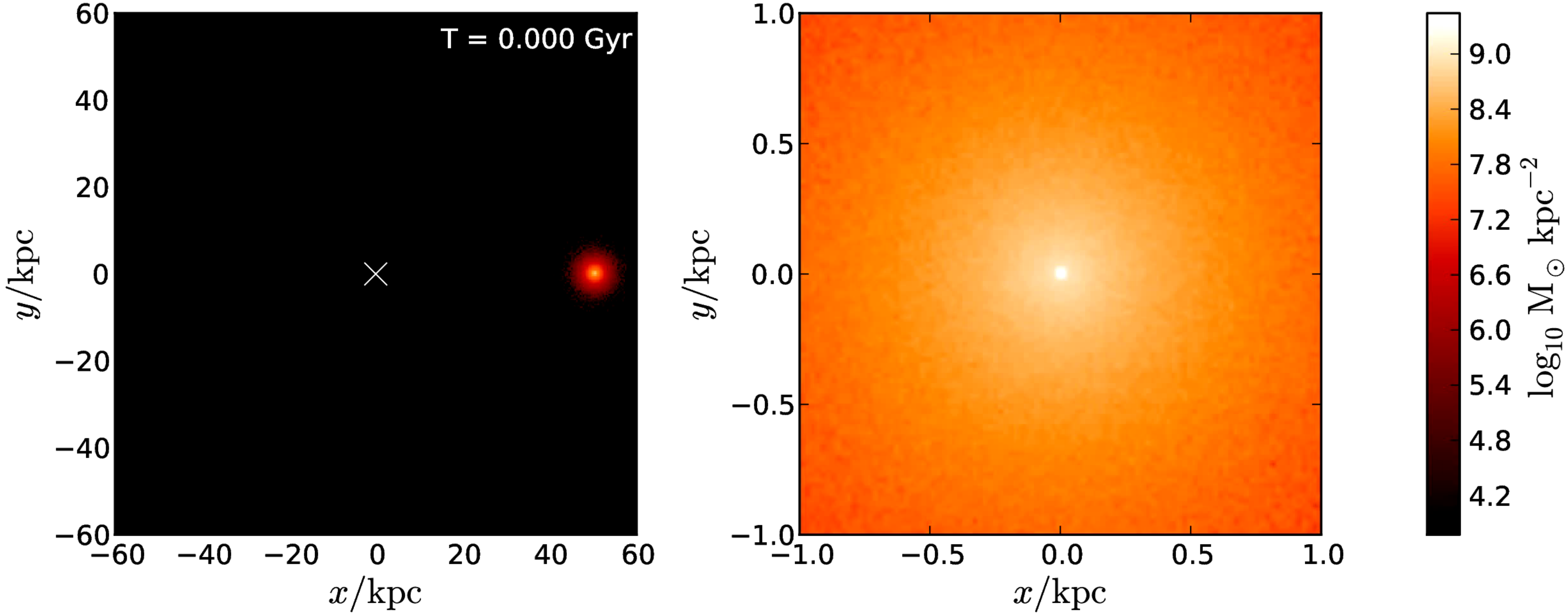


from Graham&Spitler (2009)

We have lots of evidence for ongoing tidal disruption of dwarf galaxies, e.g. in the Milky Way in the case of the M54/Sagittarius system.



NUCLEAR CLUSTER LIBERATION DURING TIDAL STRIPPING



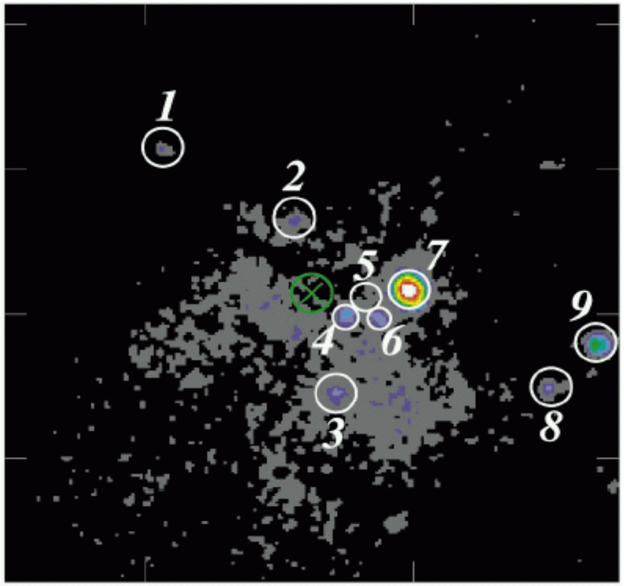
from Pfeffer et al. (2013)

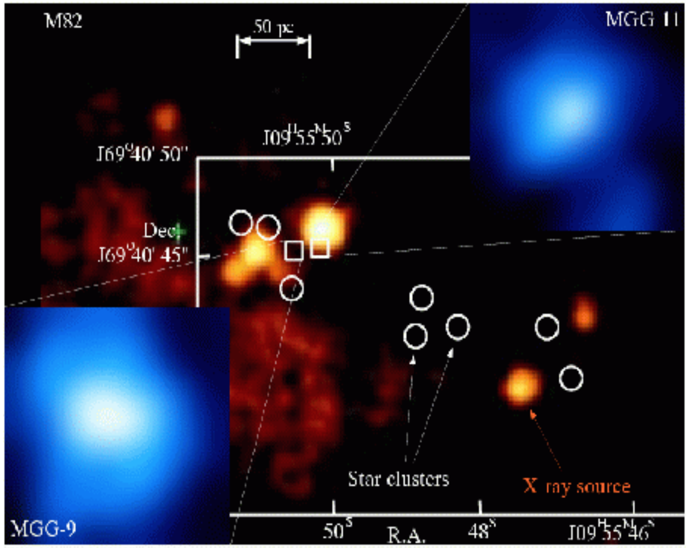
Formation of Massive Black Holes in Star Clusters

- Observations show that external galaxies contain very bright, so-called ultraluminous X-ray sources (ULX) with $L_X > 10^{39}$ erg/s.

- Matsumoto et al. (2001) for example found an ULX at the center of the starburst galaxy M82 with an Eddington luminosity corresponding to a black hole of several hundred solar masses.

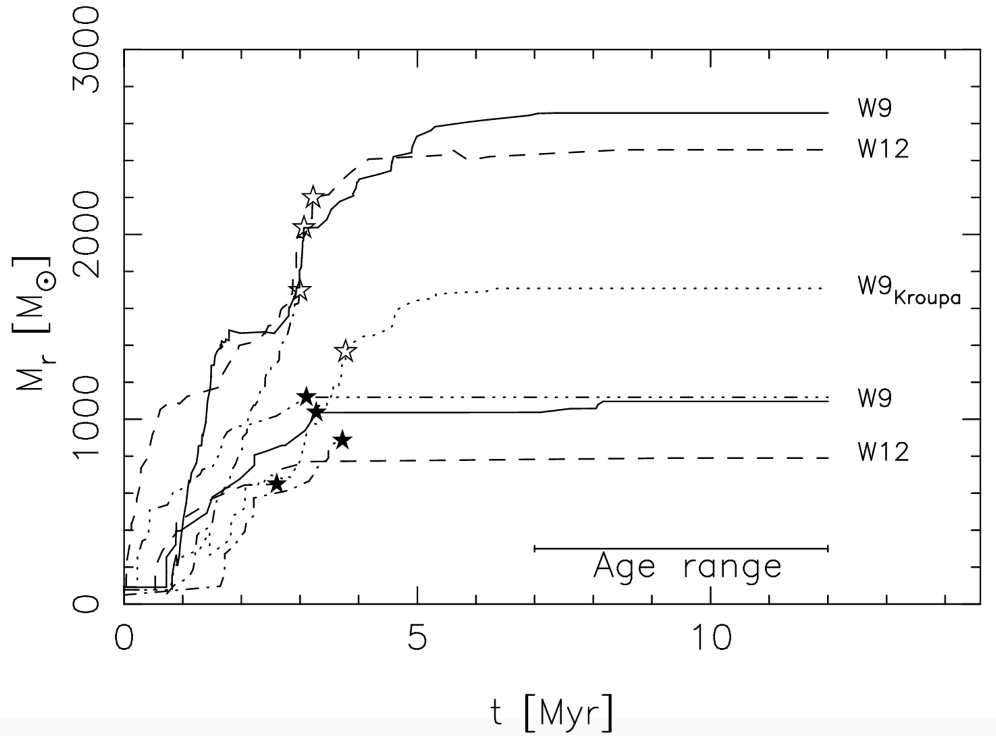
- Optical follow-up observations show that the position of the ULX coincides with that of a young luminous star cluster called MGG-11.





Formation of Massive Black Holes in Star Clusters

- Portegies Zwart et al. (2004) followed the evolution of MGG-11 by N-body simulations, including stellar evolution and the collision of stars.
- They found that heavy mass stars sink into the cluster center as a result of dynamical friction and that runaway merging of stars occurs in the center of MGG-11.
- Including mass loss due to stellar evolution might however prevent the formation of massive stars and black holes (Glebbeek et al. 2009).



Black Holes:

Stellar-mass black holes (SBHs):

$(1\ M_\odot < m_{BH} < 100\ M_\odot)$

Form as the end-product of stellar evolution.

Intermediate-mass black holes (IMBHs):

$(100\ M_\odot < m_{BH} < 10^5\ M_\odot)$

No clear evidence for their existence. Might form in dense star clusters through stellar collisions.

Supermassive black holes (SMBHs):

$(10^5\ M_\odot < m_{BH} < 10^{10}\ M_\odot)$

Exist in the centres of most major galaxies.

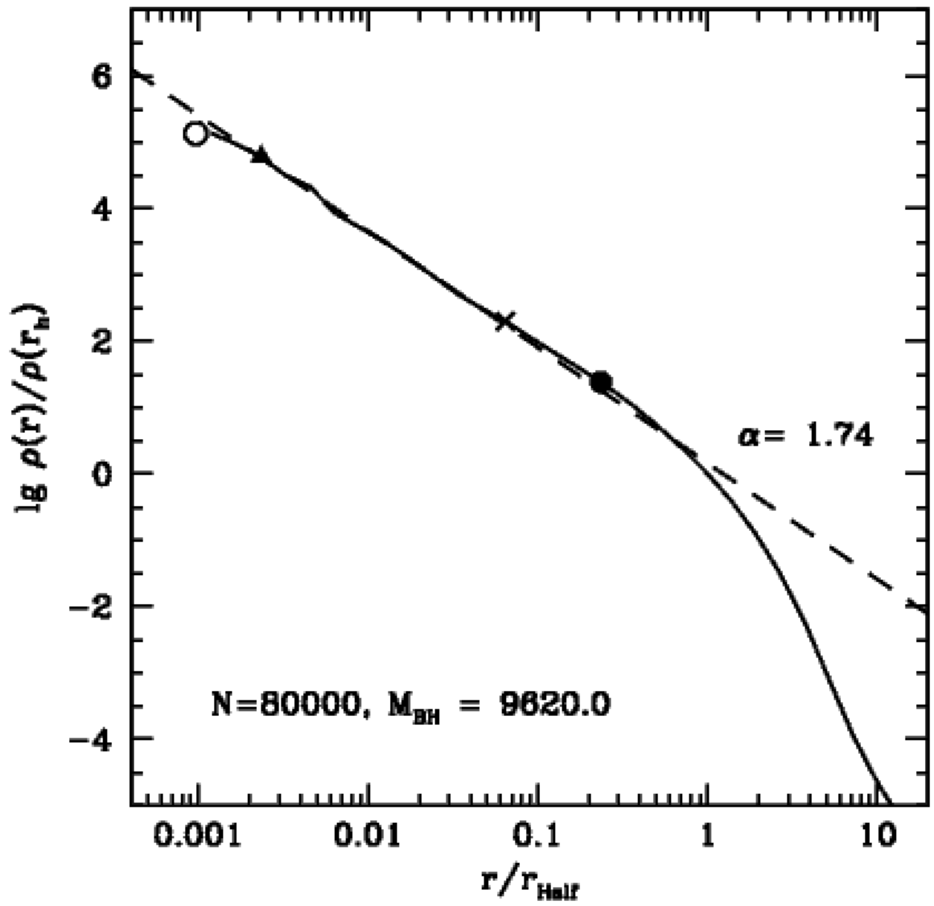
MASSIVE BLACK HOLES

Massive black hole adds 1/r-potential to the centre of the cluster.

This changes the way stars arrange themselves when cluster goes into core-collapse.

Cluster produces what is called a Bahcall&Wolf (1976) cusp which has

$$\rho \sim r^{-1.75}$$

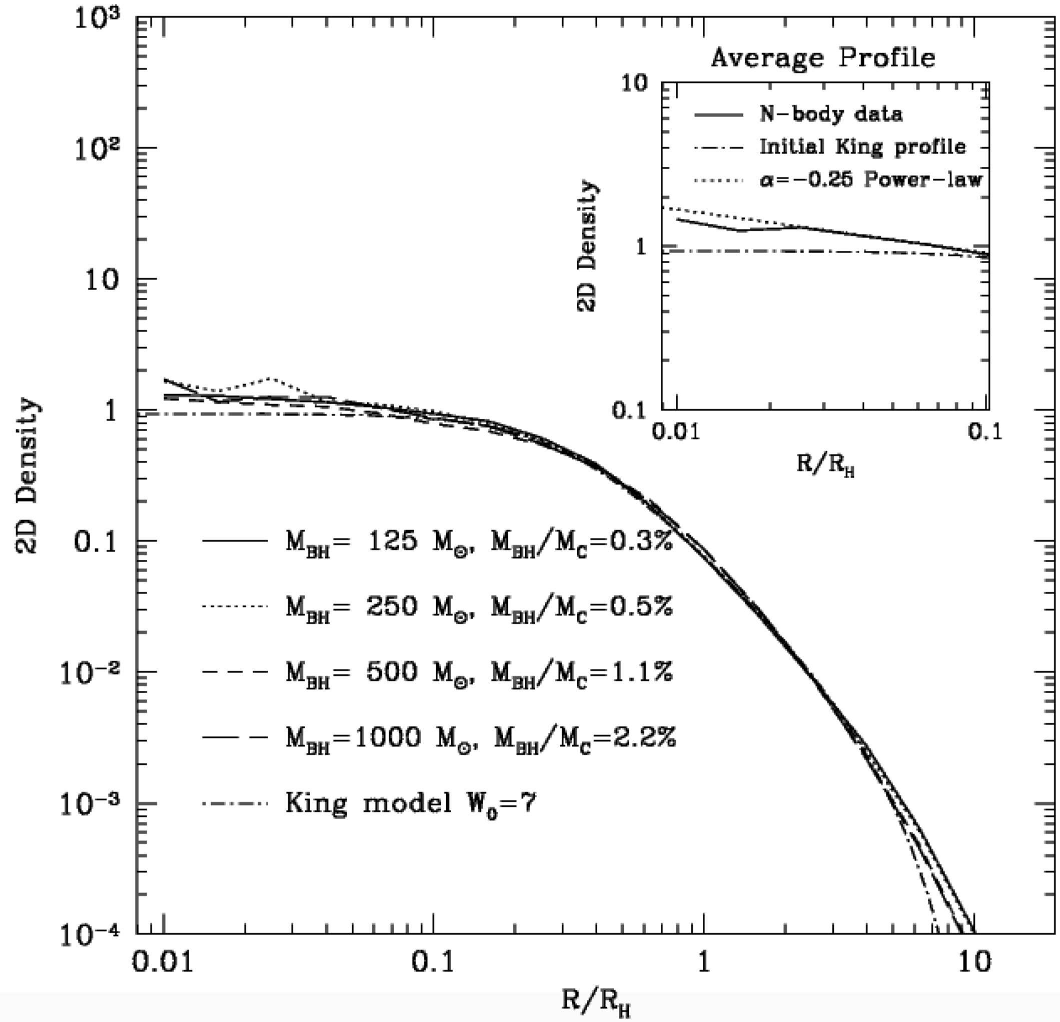


from Baumgardt et al. (2004a)

MASSIVE BLACK HOLES

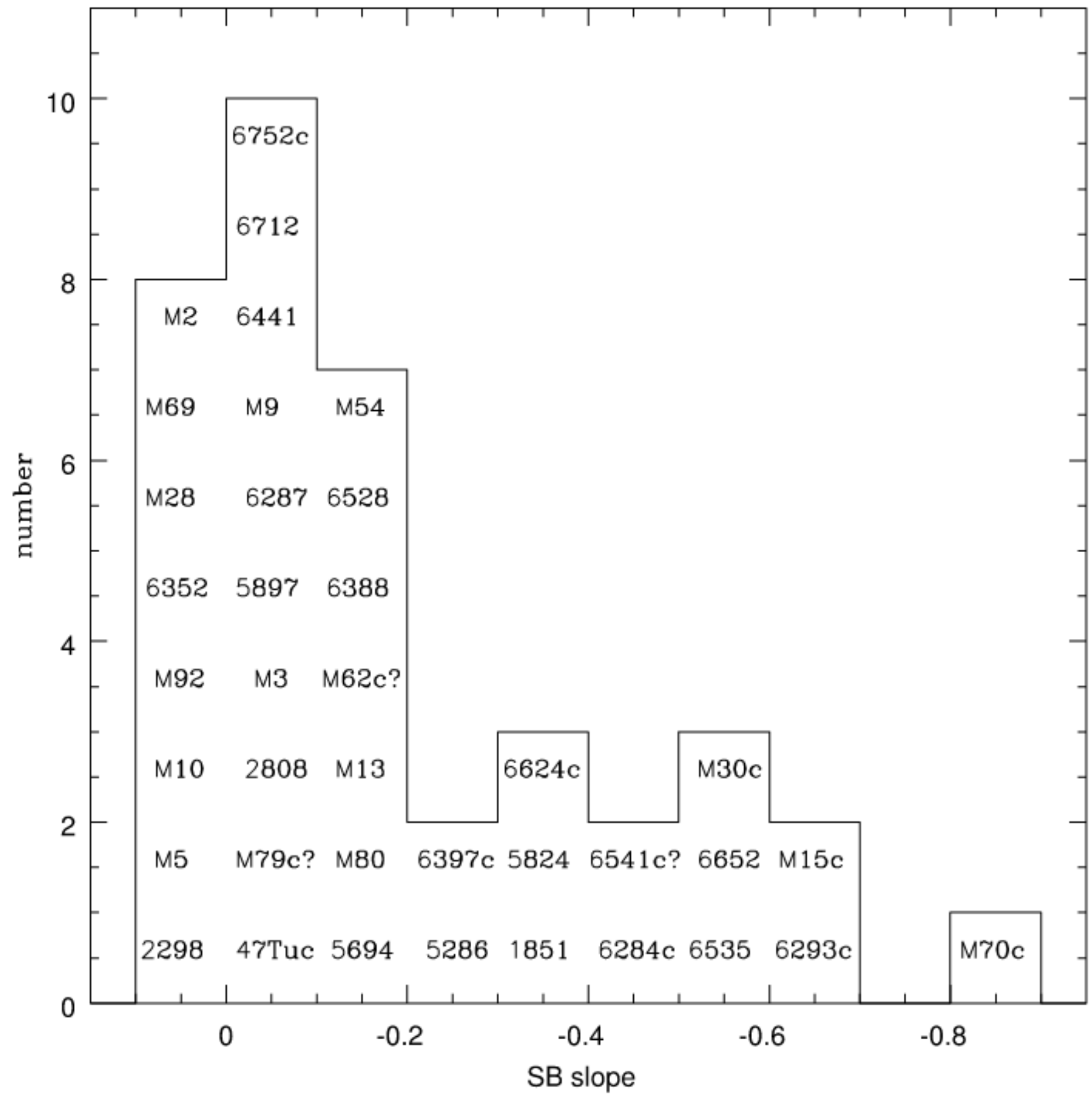
When a globular cluster is seen in projection, this leads to a very weak cusp in the density profile of the giant stars, i.e. $\rho \sim r^{-0.25}$.

For a massive enough black ($M_{BH}>10^4\ M_\odot$) it should be possible to see this cusp.



from Baumgardt et al. (2005)

CENTRAL SB SLOPES OF GALACTIC GCS



from Noyola & Gebhardt (2006)

MASSIVE BLACK HOLES

Near the black hole stars move mainly in the potential of the black hole. Very far from the black hole, stars move mainly In the potential field of the other cluster stars.

The radius where one has moves from one regime to the other is called the **influence radius** of the black hole.

It can be estimated as:

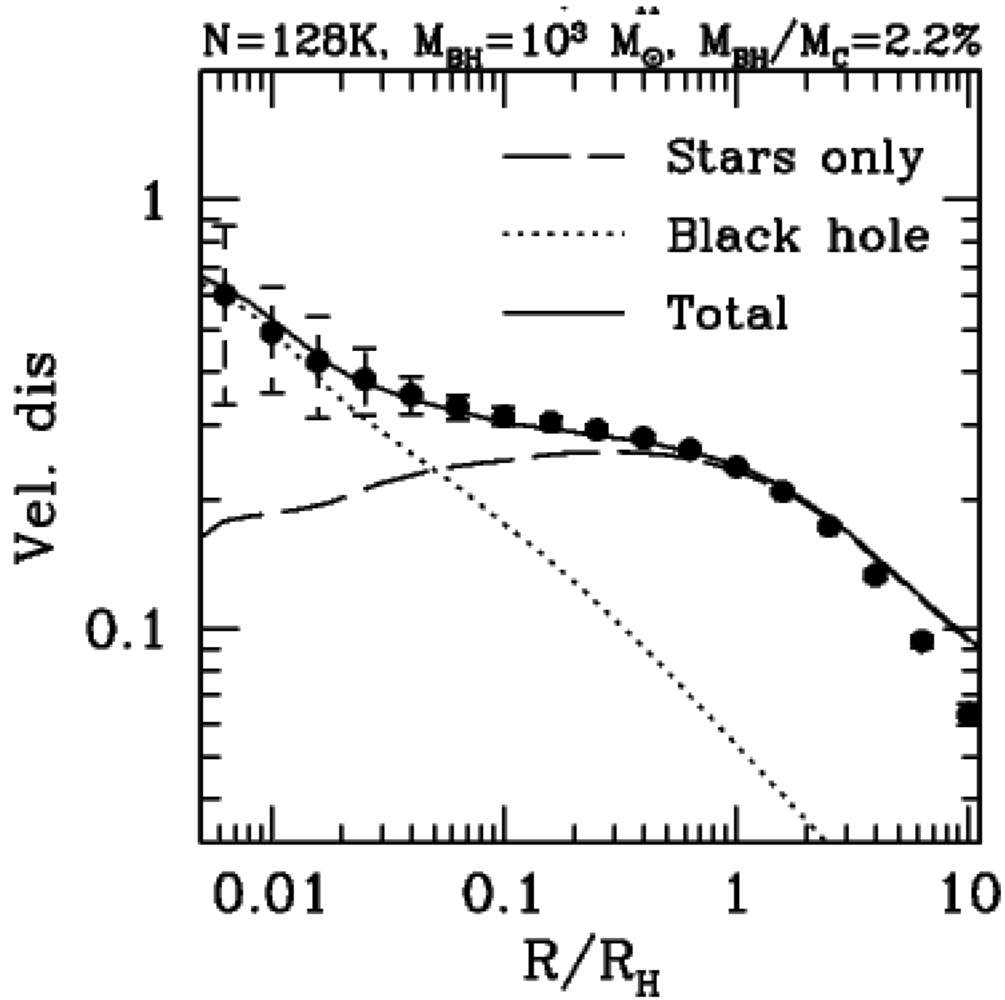
$$r_h = \frac{GM_{BH}}{\sigma^2}$$

where σ is the velocity dispersion of the stars in the core of the galaxy.

MASSIVE BLACK HOLES

The challenge in detecting a central massive black hole is to have a good enough spatial resolution to resolve the influence radius of the black hole.

In globular clusters, an additional challenge is to have enough bright stars within the influence radius!



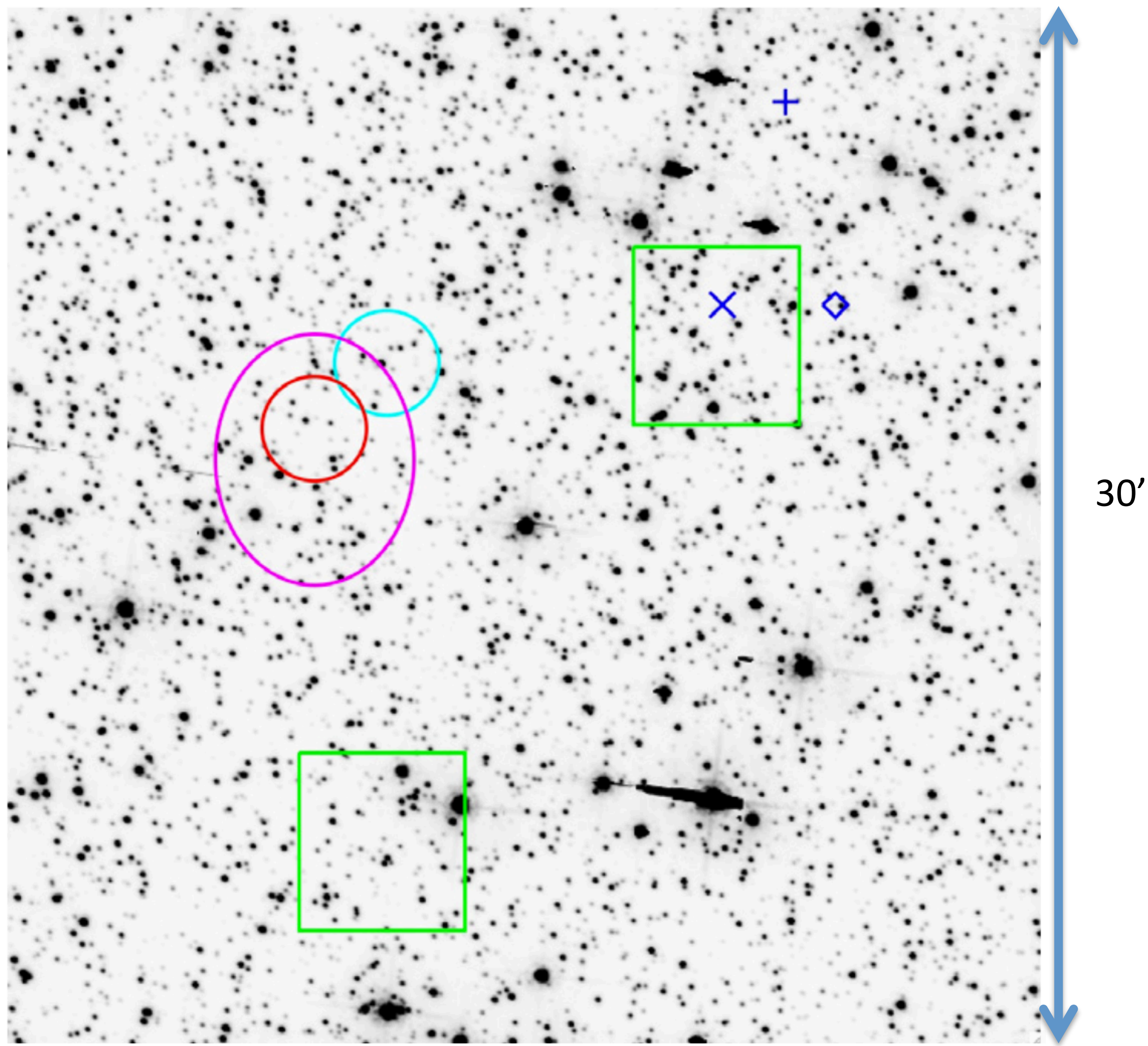
Omega Cen

Largest galactic globular cluster, mass is around 2 10^6 $M_\odot$.

Strong indications for an iron and age spread of the cluster stars.

These spreads are not observed for other globular clusters. Could indicate that Omega Cen is the nucleus of a disrupted dwarf galaxy.

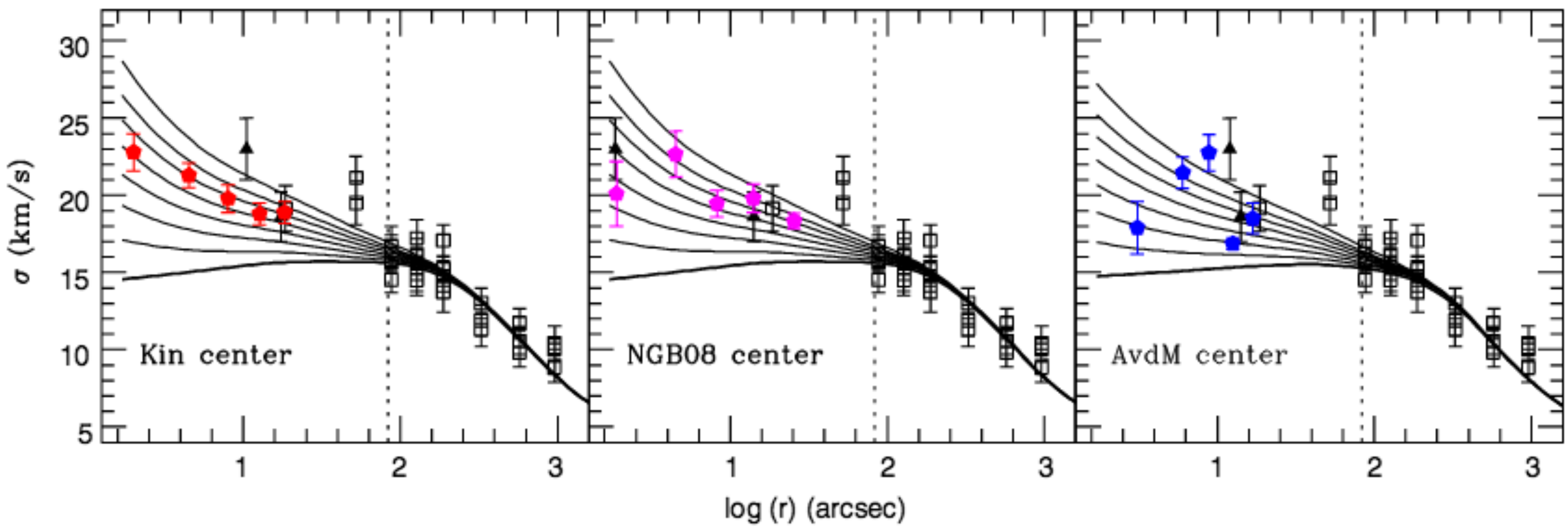
Determination of the density centre in Omega Cen is problematic due to the large, low-density core of this cluster.



from van der Marel & Anderson (2010)

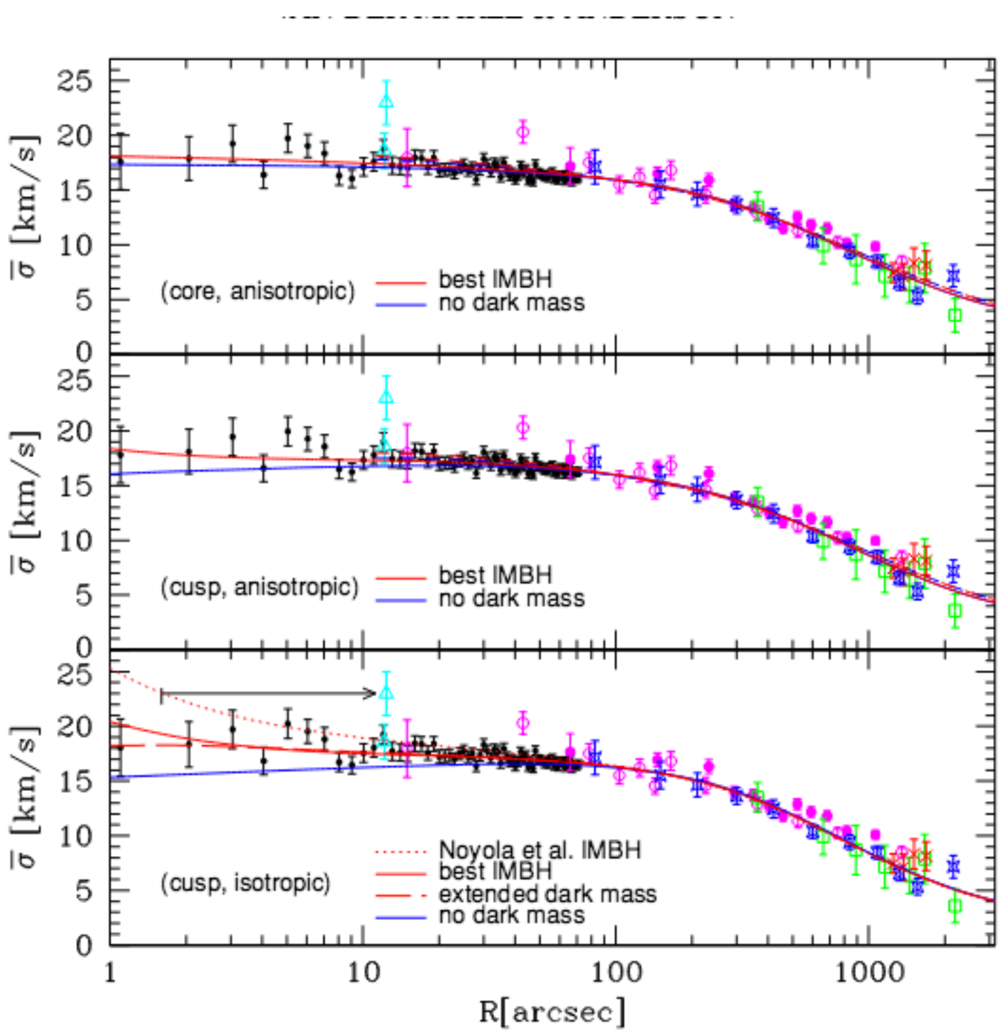
An IMBH in the globular cluster Omega Cen ?

Noyola et al. (2008, 2010) obtained radial velocity and surface brightness data for Omega Cen. They found a central rise in the velocity dispersion profile and a best-fitting black hole mass of ~40,000 $M_\odot$ depending on which position is chosen for the centre.



An IMBH in the globular cluster Omega Cen ?

- van der Marel & Anderson (2010) found a constant density core in both the surface brightness and velocity dispersion profile.
- They found an 1σ upper limit of about 12,000 $M_\odot$ for any possible black hole.



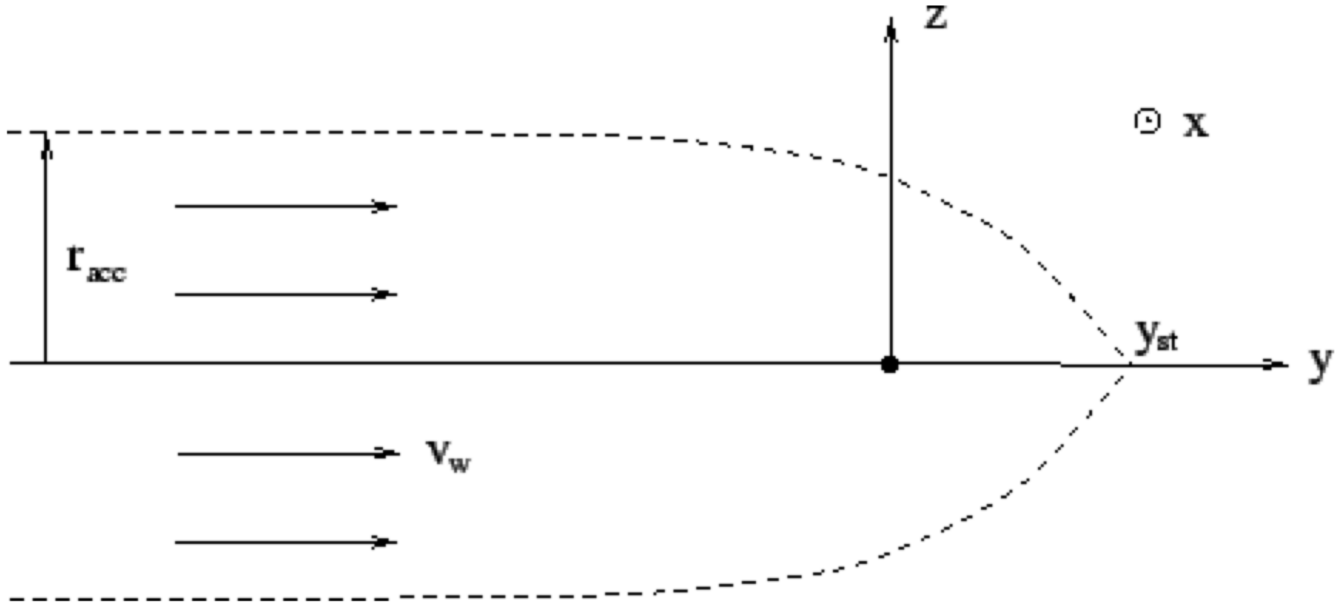
Summary of black hole searches in Local Group GCs (I)

Cluster	Mass limit		Paper
M15	$(3.9\pm2.2) \bullet 10^3\ M_\odot$	Radial Velocity	Gerssen et al. (2002)
	No black hole	RV+SB	Baumgardt et al. (2003a)
	No black hole	Radial velocity	den Bock et al. (2014)
G1	$(2.0\pm0.8) \bullet 10^4\ M_\odot$	Radial Velocity	Gebhardt et al. (2001)
	No black hole	Radial velocity	Baumgardt et al. (2003b)
	$(1.8\pm0.5) \bullet 10^4\ M_\odot$	Radial Velocity	Gebhardt et al. (2005)
Omega Cen	$(4.0\pm0.8) \bullet 10^4\ M_\odot$	Radial Velocity	Noyola et al. (2008)
	$(4.7\pm1.0) \bullet 10^4\ M_\odot$	Radial Velocity	Noyola et al. (2010)
	$<1.2 \bullet 10^4\ M_\odot$	Proper motions	Anderson&van der Marel (2010)
	$\sim5.0 \bullet 10^4\ M_\odot$	RV+PM+N-body	Jalali et al. (2012)
	No black hole	X-ray emission	Haggard et al. (2013)
NGC 6266	$<3 \bullet 10^3\ M_\odot$	Proper motions	McNamara et al. (2012)
M71	$<2 \bullet 10^2\ M_\odot$	Proper motions	Samra et al (2012)
NGC 2808	$<1 \bullet 10^4\ M_\odot$	Radial velocities	Lützgendorf et al. (2012)

Summary of black hole searches in Local Group GCs (II)

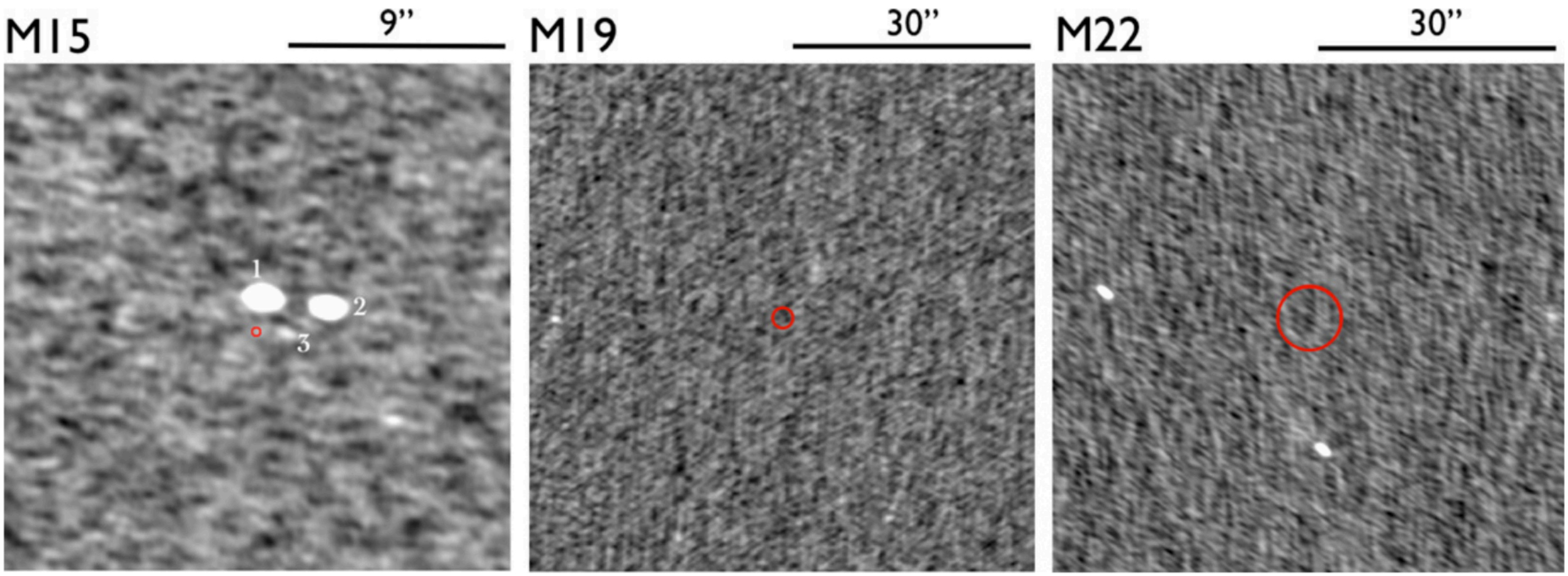
Cluster	Mass limit		Paper
NGC5286	$(3.9 \pm 2.0) \bullet 10^3\ M_\odot$	Radial Velocity	Feldmeier et al. (2003)
47 Tuc	$<1.5 \bullet 10^3\ M_\odot$	RV+PM	McLaughlin et al. (2006)
M54	$9.4 \bullet 10^3\ M_\odot$(?)	Radial velocities	Ibata et al. (2009)
NGC 6388	$5.7 \bullet 10^3\ M_\odot$	Surface density	Lanzoni et al. (2007)
NGC 6388	$(1.7 \pm 0.9) \bullet 10^4\ M_\odot$	Radial velocity	Lützgendorf et al. (2011)
NGC 6388	$<2.0 \bullet 10^3\ M_\odot$	Radial velocity	Lanzoni et al. (2013)
NGC 6388	$(2.8 \pm 0.4) \bullet 10^4\ M_\odot$	Radial velocity	Lützgendorf et al. (2015)

Detecting black holes through Bondi-Hoyle accretion



Gas that passes a black hole is accelerated towards it. At the stagnation point, velocity of gas is equal to escape velocity so that all gas inside this point will be accreted. Accreting black hole should become visible in radio and X-ray wavelengths.

Detecting black holes through Bondi-Hoyle accretion



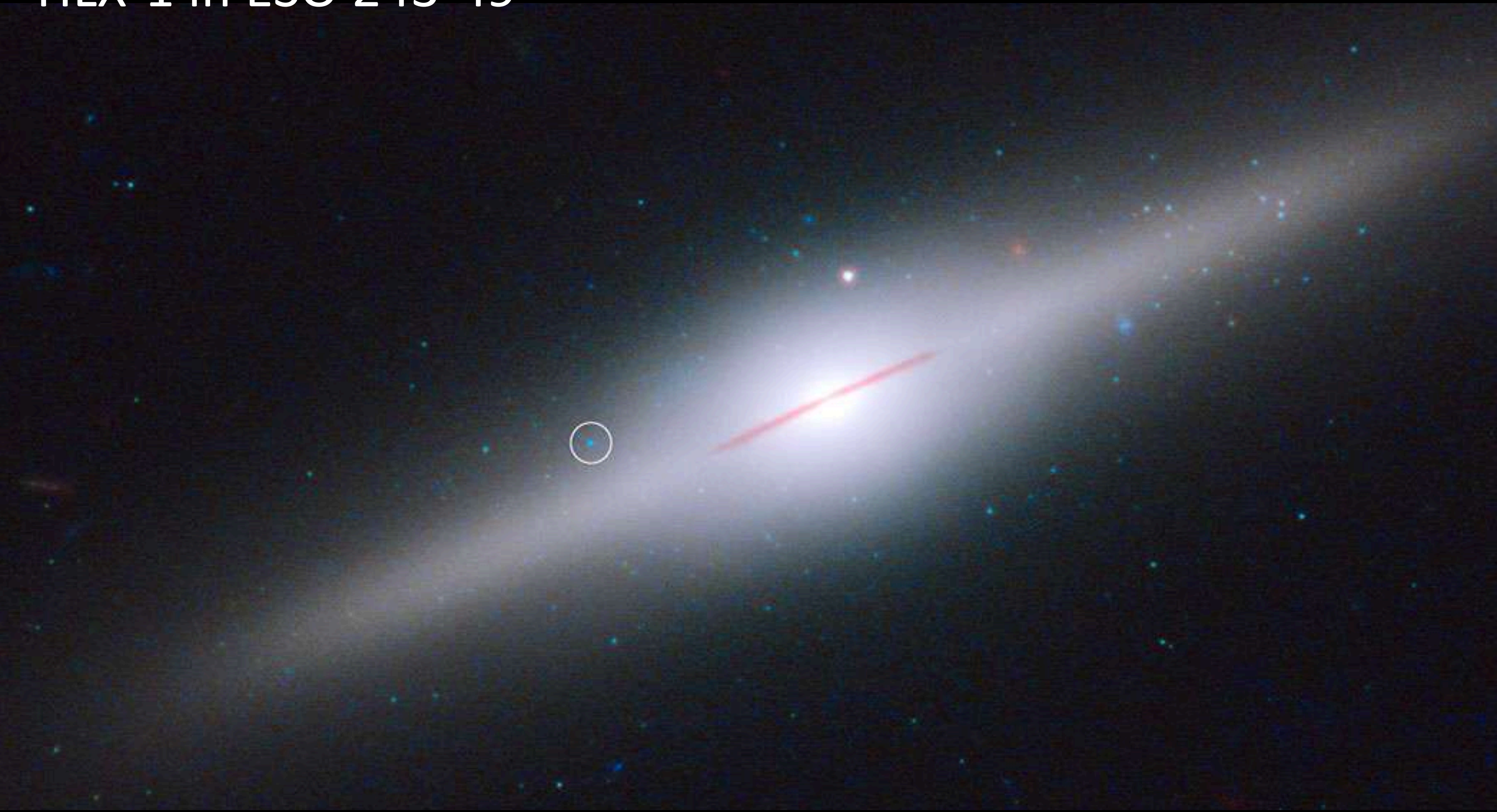
from Strader et al. (2012)

Summary of black hole searches in Local Group GCs (III)

Cluster	Mass limit		Paper
NGC 6093	$<1.5 \cdot 10^3\ M_\odot$	Radio emission	Bash et al. (2008)
NGC 6266	$<3.0 \cdot 10^3\ M_\odot$	Radio emission	Bash et al. (2008)
M15	$<1.0 \cdot 10^3\ M_\odot$	Radio emission	Bash et al. (2008)
M15	$<9.8 \cdot 10^2\ M_\odot$	Radio emission	Strader et al. (2012)
NGC 6273	$<7.3 \cdot 10^2\ M_\odot$	Radio emission	Strader et al. (2012)
NGC 6656	$<3.6 \cdot 10^2\ M_\odot$	Radio emission	Strader et al. (2012)
NGC 6093	$<3.6 \cdot 10^3\ M_\odot$	Radio emission	Maccarone & Servillat (2008)
NGC 6388	$<1.5 \cdot 10^3\ M_\odot$	Radio emission	Cseh et al. (2011)

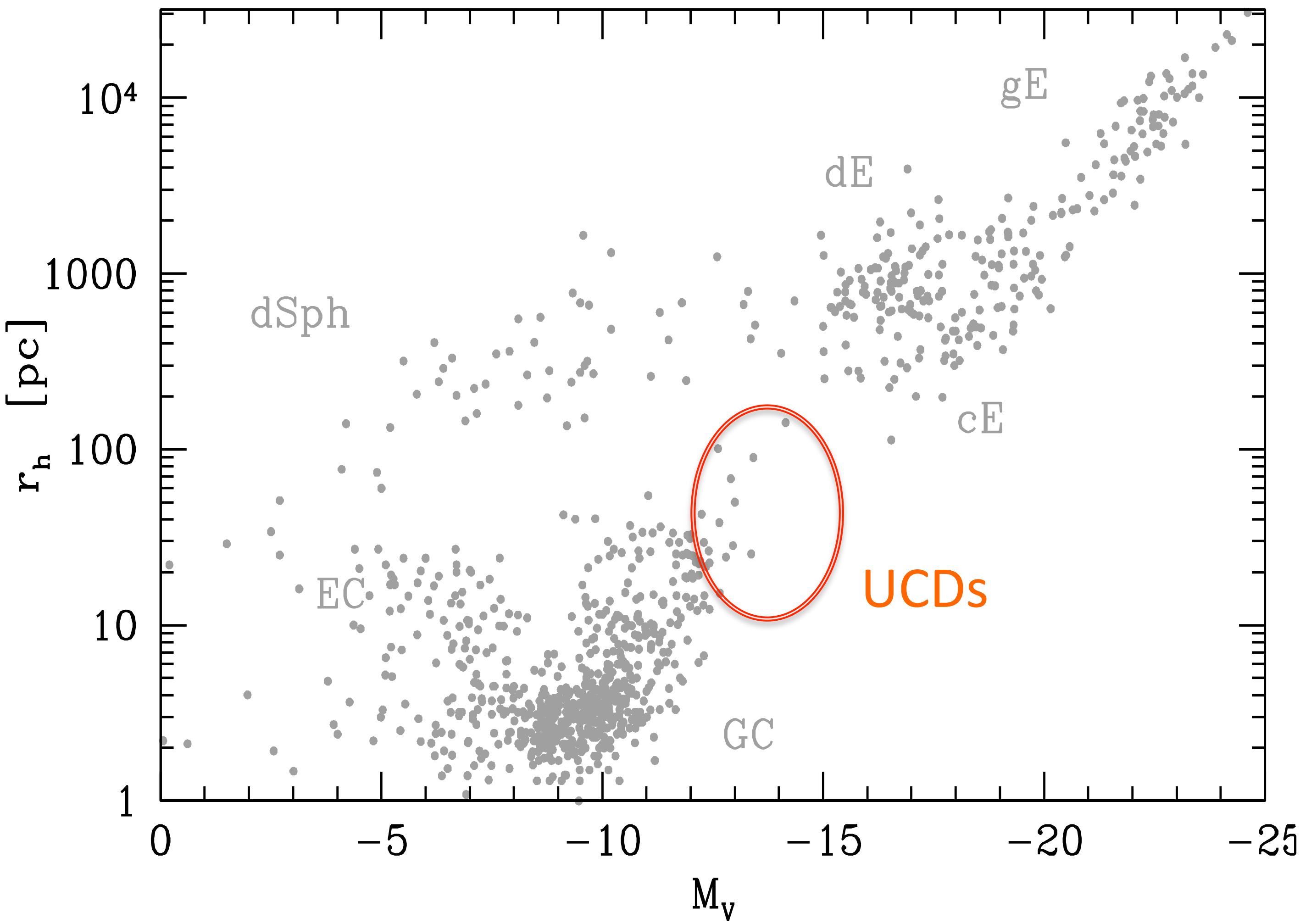
These non-detections either indicate that IMBHs do not exist in the studied clusters , that the cluster centers are gas free or that IMBHs accrete extremely inefficiently.

HLX-1 in ESO 243-49



Discovered by Farrell et al. (2009). Mass of the black hole is probably in the 10^4 to 10^5 $M_{\odot}$ range. Black hole was probably at the center of a disrupted dwarf galaxy (Farrell et al. 2012).

What are Ultra-compact dwarf galaxies?



from Brodie et al. (2013)

M60-UCD1

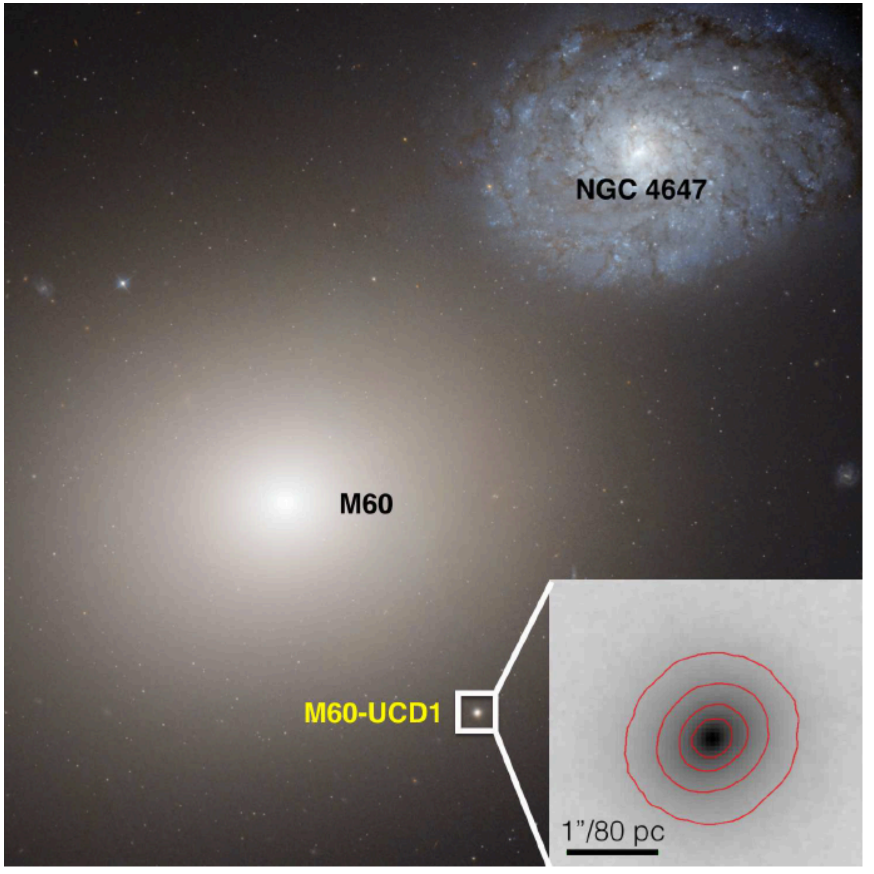
- Discovered by Strader et al. (2013).

- Brightest UCD found in the Virgo cluster so far.

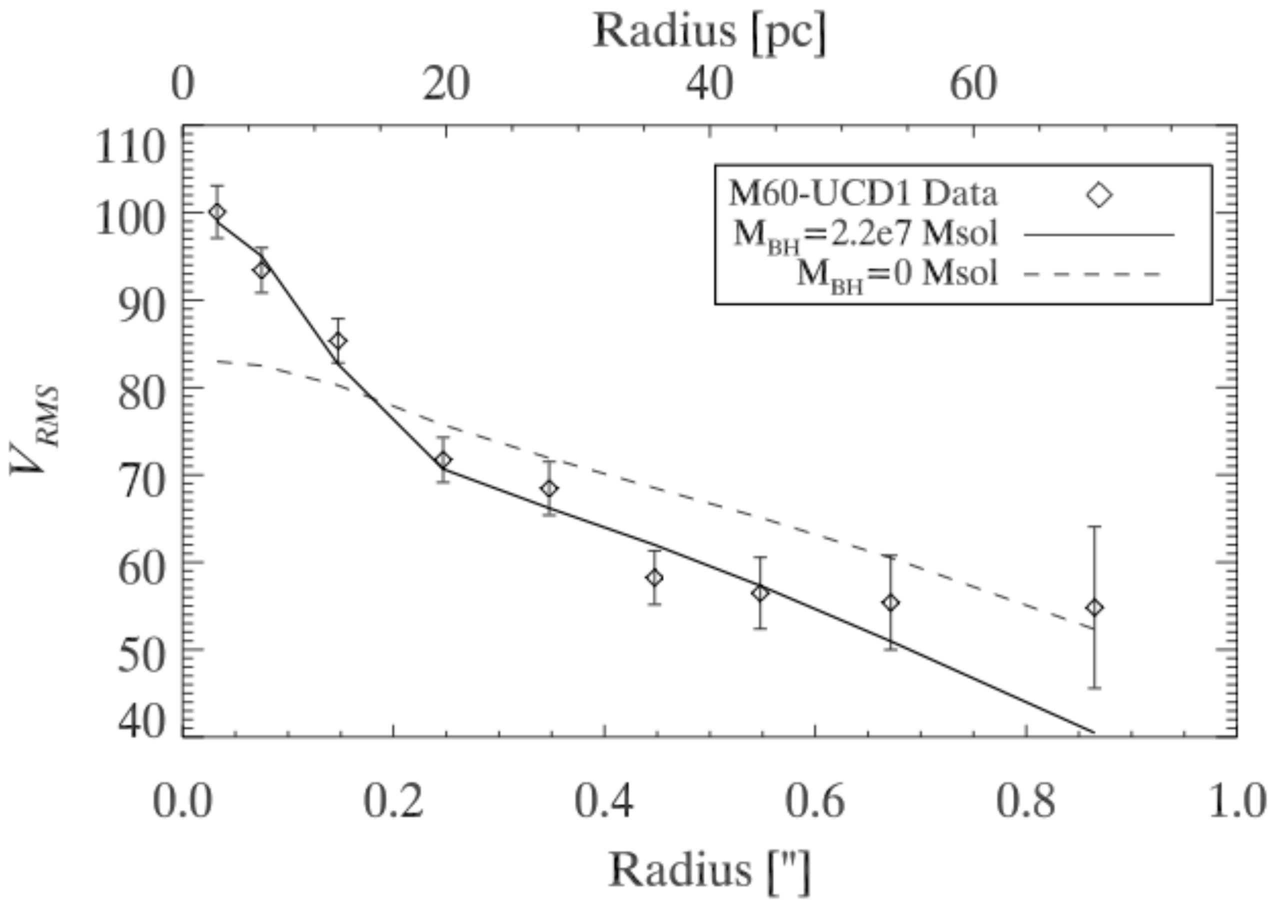
- M_V=-14.2, r_e = 24 pc, σ=68 km/sec

- The measured velocity dispersion implies a total mass of $\approx 2 \cdot 10^8 M_\odot$ and M/L value of M/L_V=4.9.

- The UCD centre hosts an x-ray source indicating the presence of an accreting black hole or neutron star.



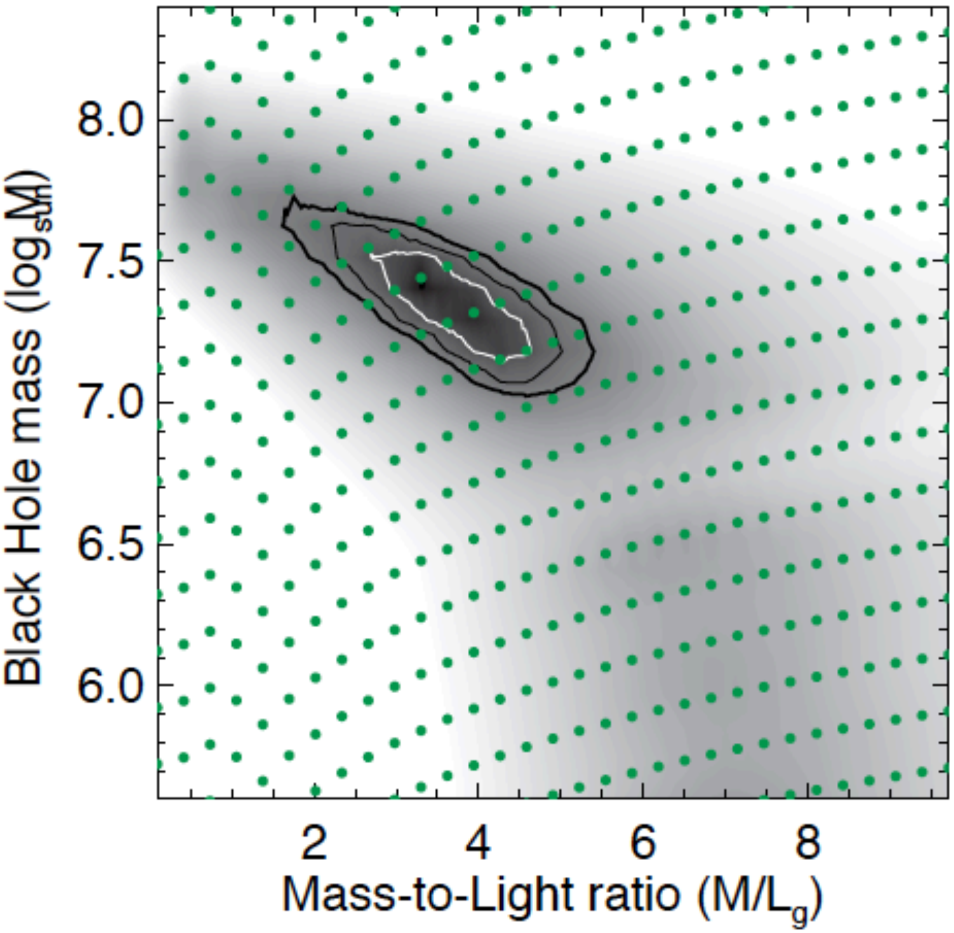
Velocity dispersion of M60-UCD1



Velocity dispersion of M60-UCD1

This rise can be explained by an SMBH with about 15% of the UCD mass !

This makes M60-UCD1 the most black hole dominated galaxy found so far.



from Seth et al. (2014)